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Pre- and Postcombustion NO_x Control for Biogas Engine With Microwave Energy

California Energy Commission

Edmund G. Brown Jr., Governor



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PREFACE

The California Energy Commission's Energy Research and Development Division manages the Natural Gas Research and Development program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

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Pre and Post-combustion Nitrogen Oxide Control for Biogas Engine With Microwave Energy is the final report for the project (Contract Number PIR-13-006) conducted by the CHA Corporation. The information from this project contributes to Energy Research and Development Division's Natural Gas Research and Development Program.

All figures and tables are the work of the author(s) for this project unless otherwise cited or credited.

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ABSTRACT

The undeveloped potential of biogas produced by California landfills, wastewater treatment facilities, dairy farms, and food processing industries is estimated at 600 megawatts. However, the exhaust from internal combustion engines fueled by biogas contains harmful pollutants such as nitrogen oxides, carbon monoxide, and volatile organic compounds. These air pollutants must be greatly reduced to comply with air quality control regulations if this fuel source is to gain widespread use. To achieve these goals, the CHA Corporation built and field tested a pre- and post-combustion nitrogen oxides control system using microwave-based biogas upgrading technology at CleanWorld's BioDigester facility at the South Area Transfer Station in Sacramento. Field testing results demonstrated that the integrated pre- and post-combustion nitrogen oxides control system met the California Air Resources Board's 2007 standards (average nitrogen oxides emissions of 5 parts per million) and the South Coast Air Quality Management District's Rule 1110.2 (average nitrogen oxides emissions of 11 parts per million). Furthermore, the microwave technology is expected to reduce the cost of controlling nitrogen oxides emissions and upgrading biogas significantly, increasing the use of biogas from small biogas sources such as dairy farms and food processing facilities. With simpler and cheaper microwave biogas upgrading and exhaust cleanup systems, additional biogas can be used to produce electricity and thermal energy to reduce natural gas use in California.

Keywords: Biogas, NO_x emission control, microwave steam reforming, H₂S removal, HALO, NO_x adsorption, carbon adsorption, microwave reactivation, NO_x-saturated GAC

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EXECUTIVE SUMMARY

Introduction

California's landfills, wastewater treatment facilities, dairy farms, and food processing industries produce nearly 85 million cubic feet per day (ft³/day) of methane (CH₄) in the form of biogas. By capturing and harnessing this biogas, the state could potentially generate 600 megawatts (MW) of power while reducing CH₄ emissions by roughly 20 million ft³/day.

Biogas can be captured by landfill gas collection systems and by anaerobic digesters fed by food waste, agricultural waste, and sludge from wastewater treatments. However, biogas produced in this way often contains contaminants such as siloxanes and sulfur components. This gas must be refined before it can be used as fuel for a stationary generator or compressed natural gas (CNG) powered vehicle engine, so it does not damage equipment or release toxic emissions. Considering tightening emission regulations and costly equipment maintenance due to biogas contaminants, an economic biogas pretreatment is required.

The South Coast Air Quality Management District's Rule 1110.2 and California Air Resources Board's (CARB) 2007 emission standards have made it challenging to meet emission standards cost-effectively. Without additional emission controls, engines running on biogas may exceed these standards. The CHA Corporation developed integrated microwave technology for pre- and post-combustion nitrogen oxides (NOx) control of biogas-powered engines. This new emission control technology will meet Rule 1110.2 and the CARB 2007 emission standards for NOx.

Project Purpose

This project demonstrated integrated microwave technology for pre- and post-combustion NOx control of biogas-powered engines to meet the 2007 CARB standards for reduced NOx emissions. It demonstrated that the technology is capable of destroying harmful contaminants in biogas and reducing emissions more cost-effectively than conventional technologies.

Project Process

The pre-combustion NOx control system had a microwave hydrogen sulfide (H₂S) removal unit followed by a microwave steam reformer. Roughly 10 percent of the biogas used to fuel the engine was processed to generate hydrogen (H₂). The H₂ was injected back into the fuel stream before combustion to create a H₂-enriched fuel gas to reduce the NOx formation in a process called *hydrogen assisted lean operation*.

The post-combustion NOx removal system consisted of an exhaust cooler and two carbon adsorbers in series. These adsorbers are filled with granular activated carbon to remove NOx from the exhaust. When the average NOx concentration in the exhaust leaving the second-stage adsorber reaches 5 parts per million (ppm), the saturated granular activated carbon in the first-stage adsorber is replaced with the newly regenerated granular activated carbon. Then, that adsorber is switched to the second-stage position. The saturated granular activated carbon is transported to the microwave reactivation facility for processing. It is expected that the granular activated carbon will be replaced and reactivated once every two to three months. An

additional benefit is that the GAC also removes sulfur dioxide (SO₂) and volatile organic compounds (VOC) from exhaust.

The microwave reactors and heater were installed in the lab to check operability and to use for the lab testing. The research team conducted the first series of lab microwave steam reforming tests using simulated tail gas to determine if tail gas could produce enough H₂ required for the pre-combustion NOx test with 30 cubic feet per minute (cfm) biogas. The result showed that tail gas could not be used to supply H₂ required for pre-combustion NOx control. Thus, CHA researchers decided to use the biogas for H₂ production.

The team conducted the second series of lab steam reforming tests using simulated biogas to determine operating parameters for the pre-combustion NOx control field test. The result indicated that the H₂ production could provide 8.8 percent of H₂ with 30 cfm biogas inlet flow rate.

For field testing, a shipping container housing all equipment for the pre-combustion NOx control was transported to the CleanWorld BioDigester site at the South Area Transfer Station located in Sacramento, California. The container was located next to the 190-kilowatt (kW) biogas-powered engine container. The pre- and post-combustion NOx control system was connected to CleanWorld's engine, CNG compressor skid, and flare.

The field testing of the pre-combustion NOx control system consisted of the H₂S removal, steam reforming, and air/fuel ratio control for NOx reduction. The H₂S removal testing was conducted using biogas withdrawn from the inlet to Bio-CNG system. The microwave steam reforming tests were conducted with biogas and CNG. The post-combustion NOx control tests consisted of one granular activated carbon bed with selective catalytic reduction, source testing, and NOx adsorption with two granular activated carbon beds without selective catalytic reduction. The field testing lasted from August to December 2016.

The mobile microwave reactivation unit was relocated to the CleanWorld BioDigester site and used to reactivate granular activated carbon used for NOx removal. The NOx and hydrocarbons released from saturated granular activated carbon were destroyed by the de-NOx and oxidation unit connected to the microwave reactivation reactor.

Project Results and Recommendations

The field testing results clearly demonstrated that pre-and post-combustion NOx control will meet not only the Rule 1110.2, but also CARB 2007 NOx emission standards. The following conclusions were drawn from pre-combustion NOx control test data as well as observations during field testing.

- Microwave energy combined with GAC was very effective in destroying H₂S on site and is a very good candidate for removing H₂S and siloxanes from biogas without using adsorbents.
- Microwave steam reforming can be applied for economical onsite H₂ generation from biogas for pre-combustion NOx control and fuel cells.

- Application of HALO is effective for biogas engines to reduce NOx formation.
- The air/fuel ratio can be increased with stable engine operation by injecting H₂ into the biogas inlet. NOx formation was reduced by more than 70 percent with stable engine operation by injecting H₂ into the biogas inlet.
- It would be difficult to reduce the NOx emissions to 11 ppm because the H₂ required would be one-third of the CH₄ in biogas. Thus, hydrogen assisted lean operation alone may not be economical to meet Rule 1110.2. Also, assisted lean operation alone will not meet the CARB 2007 NOx emission standards.

The following conclusions were drawn from post-combustion NOx control test data as well as observations during field testing.

- Post-combustion NOx control using two granular activated carbon beds in series was very effective to meet Rule 1110.2 and the CARB 2007 NOx emission standards.
- Two GAC beds in series is also an efficient method to assist existing selective catalytic reduction to meet CARB 2007 NOx emission standards of 5 ppm.
- Reducing superficial gas velocity through the granular activated carbon bed increased the NOx removal rate. When the superficial gas velocity was reduced from 25 ft/min to 15 ft/min, the NOx removal rate increased three times (from 1.12 ft³/h to 3.37 ft³/h).
- Granular activated carbon beds completely removed ammonia, sulfur dioxide (SO₂) and VOCs from exhaust.
- NOx-saturated granular activated carbon was reactivated in the microwave mobile unit and microwave reactivation could reduce the operating cost of post-combustion NOx control.
- NOx and VOCs released from microwave reactivation of saturated GAC were destroyed in the De-NOx and oxidizer microwave reactors.
- The integrated post-combustion NOx control with microwave reactivation is the most cost effective.

CHA and Technikon are working to commercialize the microwave reactivation technology. Technikon is developing the business plan that will include the value proposition, market opportunity, the business strategy to assess the market opportunity, competitive threat, financial projections and investment needs to execute the business plan. CHA is working to scale up the microwave reactivation system to 300 lb/horsepower with consistent quality output and automation. The commercial operation will start to reactivate the NOx-saturated and H₂S-saturated carbon at the South Area Transfer Station BioDigester site.

The CHA Corporation recommends the following next steps to advance the technology and determine its potential:

- Conduct the field-testing of microwave-based biogas cleanup to determine its economic and technical feasibility.

- Perform a detailed technical and economic feasibility study for reactivating NOx and VOC saturated granular activated carbon on a central facility close to biogas producers.
- Install an integrated post-combustion NOx control with microwave reactivation and demonstrate that this technology could be the best available control technology for CARB 2007 NOx emission standards.

Benefits to California

This microwave-based technology makes biogas cleaner and more acceptable in populated communities. Meeting the CARB 2007 NOx emission standards will eliminate 221 pounds of NOx from every 1 million cubic feet of biogas used for power generation. Integrated postcombustion NOx control with microwave reactivation is the most cost effective NOx removal technology. The NOx removal cost of this technology is 1.8 cents per kWh power produced, which is lower than the special feed-in-tariff of 6 to 9 cents per kWh.

With simpler and cheaper microwave biogas upgrading and exhaust cleanup systems, additional biogas can be used to produce electricity and thermal energy, reducing natural gas use and the release of greenhouse gas (CH₄) from manure digesters and landfills. Central or onsite microwave reactivation technology will allow recycling of activated carbon, reducing the greenhouse gas emissions attributed to the manufacturing of activated carbon and disposal of used carbon. The integrated postcombustion NOx control with microwave reactivation allows new biogas producers to meet CARB NOx emission standards with low NOx removal cost. This will create more biogas production facilities, generating more green jobs.

CHAPTER 1:

Why This Project Is Important

1.1 Background and Overview

The U.S. EPA estimates a potential of 5,500 megawatts (MW) from biogas generated from landfills, wastewater treatment digesters, food waste digesters, and animal waste digesters in the United States¹ Development of biogas resources in California is an important component of improving statewide distributed generation and reducing emissions of greenhouse gases such as CH₄.

According to research by the California Energy Commission presented in 2007, biomass power plants produced 6,259 gigawatt hours (GWh) of electricity for Californians, representing 3.42% of California's total power production.² This power was produced by methane (CH₄) from landfills, wastewater treatment, animal manure, food waste, and solid fuels such as wood from forest slash and lumber waste. These solid fuels do not require hydrogen sulfide (H₂S) cleanup that landfill, wastewater, and animal produced CH₄ do, so it will not be included as CHA Corporation's potential customer base. Of the 132 biomass power plants in California with a gross capacity of 985 MW, 30 power plants use solid fuel combustion². A total of 102 biogas facilities are left with a gross capacity of 345 MW as potential users of CHA technology. An economic biogas pretreatment is required considering tightening emission regulations and costly equipment maintenance due to biogas contaminants.

The U.S. Environmental Protection Agency (EPA) AgStar Digester Database reports an estimated 1.4 million cubic feet of biogas produced per day by California livestock digesters, for the 8 of 14 digesters where these data were available. Another U.S. EPA report from 2011 shows 33 wastewater digester sites in California with a total capacity of 62.67 MW.

1.1.1 Contamination in Biogas

Siloxanes and H₂S are the most troublesome biogas contaminants. During combustion, siloxanes are converted into silicates (SiO₂) which damage turbine blades, form harmful scales that increase engine wear, and foul post combustion catalysts. The H₂S and halogenated compounds in the gas form corrosive acids including sulfuric acid (H₂SO₄) and hydrochloric acid (HCl). Even small quantities of sulfur dioxide (SO₂) in engine exhaust will poison catalytic emission control systems otherwise suitable to reduce nitrogen oxide (NOx) on a natural gas fired engine.

According to a 2007 study by Bothi of Cornell University, biogas produced at the dairies contained H₂S concentrations between 1,000 and 3,600 ppm, where no food waste was added

1 Sloe, Jon, Biogas, A Growing Niche for Distributed Generation, E-Source, DE-21, May 2003

2 Williams, 2007 (from staff presentation), California Energy Commission, <http://www.energy.ca.gov/biomass/>

and where farm water did not have high sulfur content. Adding food waste produced lower H₂S concentrations while sulfurous farm water increased the H₂S concentration, in some cases greater than 7,000 ppm.³

Commercially available media will adsorb H₂S, siloxanes, organic halides, and long chain hydrocarbons in biogas, however are expensive and difficult to regenerate. Lower-cost material, such as carbon, is buried or burned when spent thereby releasing contaminants back into the environment. Current media regeneration methods are complicated and expensive and can involve additional waste streams or flares.

CHA Corporation's H₂S removal system would likely begin installations locally, serving the biogas cleanup needs of projects close to its home base in Sacramento, California. According to the AgSTAR National Mapping Tool⁴ and the U.S. EPA's Landfill Methane Outreach Program⁵, there are nine operational dairy digesters and 17 operational landfill gas projects within 100 miles of Sacramento.

1.1.2 Hydrogen Assisted Lean Operation (HALO)

The rate of NO_x formation in internal combustion (IC) engines is governed by in-cylinder peak gas temperature and in-cylinder oxygen concentration⁶, both are affected by the air/fuel (A/F) ratio. The A/F ratio is the total air to stoichiometric air. For any fixed engine setting, the in-cylinder gas peak temperature is highest at an A/F ratio of 1.1. As A/F ratio increases, the O₂ concentration of exhaust increases and the peak temperature decreases. A slightly rich A/F ratio causes high in-cylinder gas temperature peaks, but combined with reduced oxygen results in lower NO_x emissions than with stoichiometric air. Maximum NO_x emissions appear when the A/F ratio is slightly lean of stoichiometric. As the A/F ratio is further increased, in-cylinder temperature decreases. The decrease of NO_x due to lower temperature overrides the increased NO_x formation from higher oxygen content, allowing for the lowest NO_x emissions at ultra-lean conditions.

Because hydrogen has wide flammability limits, it is used to ignite ultra-lean mixtures and accelerate the burn rate, thereby extending the lean operating limit. Many groups have studied hydrogen assisted lean operation (HALO) for natural gas fired engines during the past 25 years.

3 Kimberly Lynn Bothi, *Characterization of Biogas from Anaerobically Digested Dairy Waste for Energy Use* (Master Thesis, Cornell University, 2007)

4 AgSTAR Database of Livestock Digesters, Environmental Protection Agency, https://www.epa.gov/sites/production/files/2016-05/agstar_database_of_livestock_digesters_may_2016.xlsx

5 "SPA's Landfill Methane Outreach Program," Environmental Protection Agency, <https://www.epa.gov/sites/production/files/2016-08/lmopdataca.xlsx>

6 Wilson, TIAX LLC, *Application of Hydrogen Assisted Lean Operation to Biogas Fueled Reciprocating Engines* <http://www.energy.ca.gov/2012publications/CEC-500-2012-064/CEC-500-2012-064.pdf>

TIAX performed extensive modeling and engine testing of HALO for natural gas fired engines⁷. It demonstrated that HALO allows stable engine operations to be achieved at ultra-lean ($A/F=2$) conditions. NOx emission of 10 ppm (0.07 g/bhp-hr) was obtained using 8% H_2 supplementation at an exhaust O_2 level of 10%. The research team understood that 8% H_2 supplement was 8% volume concentration in the natural gas.

Later researchers found that 8% H_2 supplement was based on low heating value (LHV) of H_2 in CH_4 . The spark ignition energy was also reduced by 22% with 13% LHV H_2/CH_4 supplement. Furthermore, TIAX assessed the feasibility of using HALO to control NOx in the exhaust of engines running on landfill biogas and a 90% NOx reduction solution by landfill gas fed to an onsite reformer to produce H_2 .⁸ The team concluded that the onsite steam reforming for H_2 production is more economical than trucking H_2 .

Under the project funded by the California Energy Commission, TIAX carried a series of scoping tests using a 75 kW engine with synthetic landfill gas and synthetic reformat prepared using bottled gases.⁹ Onsite H_2 generation using biogas and air for steam reforming will be critical to demonstrate the application of HALO to landfill biogas.

With 6% LHV H_2/CH_4 supplement, 20-30 ppm NOx emission was obtained at 7.5-8% O_2 in the engine exhaust. When the LHV H_2/CH_4 increased to 7.5-15%, the NOx emission was reduced to 5-10 ppm at 8-10% O_2 concentration. Its test results demonstrated that the biogas engine could operate for sustained period at 100% excess air with engine-out NOx emissions at 0.11 pound per megawatt-hour (MWh) or 10 ppm. TIAX, however, did not test on an engine fed with landfill biogas using onsite H_2 production.

The LHV H_2/CH_4 of 7.5-15% represents the concentration of H_2 in CH_4 of 22.5-45%. A 190-kW engine uses 50 cfm biogas with 60% CH_4 content. To maintain 7.5-15% LHV H_2/CH_4 , 6.75-13.5-cfm of H_2 must be supplied to reduce the NOx emission to 10 ppm. This high H_2 supplement will make it very expensive to use HALO alone to meet 11 ppm NOx emission standards. Economic on-site H_2 generation may be the only option for HALO to be used to reduce NOx emission.

HALO faces two barriers to market advancement for pre-combustion NOx control of biogas IC engines. The first is the high cost of supplying H_2 to biogas engines located at dairy farms, landfill sites, and wastewater treatment plants. The delivered price of compressed H_2 ranges between \$12-\$17.5/kg H_2 . Therefore, the H_2 must be generated from biogas onsite for HALO to be economically competitive for NOx control.

7 "Hydrogen Assisted Lean Operation", presented by TIAX at 3rd Annual Advanced Stationary Reciprocating Engine Meeting, June 28-30, 2006

8 "Hydrogen Assisted Lean Operation", presented by P. Couch et al of TIAX at 4th Annual Advanced Stationary Reciprocating Engine Meeting, September 18-19, 2007, Downey, California

9 *Final Report for Application of Hydrogen Assisted Lean Operation to Biogas Fueled Reciprocating Engines (BioHALO)*, prepared for California Energy Commission, prepared by TIAX LLC, CEC-500-2012-064, May 2012

Steam reforming is the best method for onsite production of H_2 for HALO. Biogas impurities including H_2S and siloxanes must be removed to protect the steam-reforming catalyst. CHA proved the microwave method for steam reforming with desulfurization in the laboratory test under a previous grant from the Energy Innovations Small Grant Program (grant number: 56938A/10-05). However, the microwave onsite H_2 production has not been previously tested in the field with biogas or tail gas.

The second barrier for HALO is that this pre-combustion technique has not previously been tested with biogas-powered engines. The use of HALO alone may not meet the CARB NOx emission standards of 5 ppm and requires the post-combustion NOx control. However, HALO could reduce NOx emission below 10 ppm which will significantly reduce the post-combustion NOx removal requirement.

1.1.3 NOx Adsorption by Activated Carbon and Carbon Regeneration.

Selective catalytic reduction is a commonly used NOx control technology, wherein a reductant such as ammonia or urea is injected into the exhaust stream of an engine as it passes through a catalyst. NOx in the exhaust reacts with reductant to produce nitrogen (N_2), water, and carbon dioxide. Some reductant can pass through the SCR system, resulting in ammonia or urea in the exhaust stream. California regulations prohibit ammonia concentrations greater than 11 ppm in exhaust, so engines using an SCR system to control NOx emissions must be able to prevent or capture this ammonia slip.

The post-combustion NOx control system uses two activated carbon beds in series to adsorb NOx from the exhaust stream of the engine. The carbon beds also adsorb ammonia leftover from the SCR. After NOx breakthrough had occurred in the first carbon bed, the carbon was reactivated in CHA Corporation's reactivation trailer, to be used for further adsorption.

1.2 Project Goals and Objectives

The overall objective of this project was to conduct a field demonstration of integrated microwave technology for pre- and post-combustion NOx control of biogas-powered engines. The project demonstrated how this technology will meet the 2007 CARB NOx emission standards.

The February 1, 2008 amendment of the South Coast Air Quality Management District's Rule 1110.2 substantially reduced emission limits for engines fueled by biogas. Hydrogen sulfide and siloxanes in biogas poison catalysts used in post-combustion NOx control methods and cause engine damage. Without additional emission controls, engines running on biogas may exceed the amended Rule 1110.2 emission standards. Because of catalyst poisoning, post-combustion NOx control methods such as SCR require an extensive biogas treatment to remove impurities. As a result, there are no engine manufacturers or post-combustion emission providers that will provide guarantees for emission controls of biogas engines that meet the Rule 1110.2 and CARB 2007 NOx emission standards.

The CHA Corporation developed integrated microwave technology for pre- and post-combustion NOx control of biogas-powered engines. This new emission-prevention technology

will directly address problems described above and meet the Rule 1110.2 and the CARB emission standards for NO_x. A microwave-based steam reforming system will produce H₂ for pre-combustion NO_x control. A two-stage adsorber will remove NO_x and other pollutants from the engine exhaust.

The goals of this project were to:

- Increase use of biogas for power generation, providing California with a renewable energy resource to meet AB 32 goals.
- Reduce air emissions by using biogas as fuel to improve public health and increase the utilization of biogas to help utilities meet AB 32 goals.
- Reduce the warm-up time of emission control equipment, reducing emissions when utilizing biogas engines to provide power during peak usage periods.
- Reduce the complexity of emissions control systems, improving the overall performance to reduce air pollutants emissions from biogas-powered engines.
- Provide a reliable H₂S removal system that can both accommodate fluctuations in H₂S concentration levels and gas production and create H₂S-free biogas for H₂ production with steam reforming to improve energy conversion efficiency.
- Ensure that the combination of pre- and post-combustion NO_x controls will meet the Rule 1110.2 and CARB 2007 standards (5 ppm NO_x emission).
- Demonstrate that the NO_x removal cost of the microwave technology is more cost-effective than the conventional post-combustion NO_x control technologies.

The objectives of this project were to:

- Conduct a field demonstration of the integrated microwave technology for pre- and post-combustion NO_x control of biogas-powered engines.
- Demonstrate that the integrated pre- and post-combustion NO_x control system will achieve the CARB 2007 NO_x emission standards of 5 ppm and remove more than 90% of SO₂ and VOC in engine exhaust.
- Achieve the following goals: 1) H₂S concentration in microwave treated biogas of less than 0.1 ppm; 2) biomethane conversion to H₂ of 70%; 3) NO_x concentration reduction by hydrogen injection (pre-combustion NO_x control) more than 70%; 4) NO_x emission less than 5 ppm; and 5) SO₂ and VOC removal more than 90%.
- Demonstrate an H₂S removal system consisting of air injection followed by microwave destruction that will completely remove H₂S from biogas for H₂ production.
- Work with potential commercialization partners to develop biogas markets for pre- and post-combustion NO_x control technology.
- Demonstrate the feasibility of producing H₂ from biogas for fuel cells.

1.3 CleanWorld BioDigester System

CleanWorld designed and built an innovative anaerobic digester biorefinery at the SATS located at 8550 Fruitridge Road, Sacramento, California. Up to 100 tons/day of organic waste collected from local restaurants, supermarkets and food-processing companies are converted through anaerobic digester (AD) technology into biogas. CleanWorld's Sacramento BioDigester generates 700,000 diesel gallon equivalents of renewable compressed natural gas (Bio-CNG) and diverts

nearly 40,000 tons of organic waste from landfills annually. The fueling station is owned and operated by CleanWorld partner Atlas Disposal. The Bio-CNG is used to fuel their waste hauling fleet in addition to city buses and other private fleet vehicles. The BioDigester facility reduces greenhouse gas emissions by 20,000 tons annually and produces 10 million gallons of fertilizer and soil amendments annually. Figure 1 is a photo of CleanWorld's Sacramento BioDigester Facility.

Figure 1: CleanWorld's BioDigester



The California Energy Commission provided an additional \$6 million in June 2012 to expand the biorefinery capacity from 25 tons/day to 100 tons/day, leveraging more than \$7.3 million in private investment including Five Star Bank, Central Valley Community Bank, California Department of Recycling and Recovery (CalRecycle) and Synergex.

The biogas consists of 45-65% CH_4 and 35-55% CO_2 . The biogas contains impurities such as H_2S and nonmethane hydrocarbons including VOCs. The H_2S and other impurities are removed by the primary H_2S scrubber charged with SulfaTreat 410 CHP and the secondary granular activated carbon (GAC) filter. The cleaned biogas flows into the membrane separator to produce the bio-CNG and tail gas that is burned in the flare.

CleanWorld has a 190 kW IC engine for power generation using a part of the biogas produced. Most of the H_2S in this biogas is removed in the primary H_2S scrubber. The CHA Corporation received a letter of support from CleanWorld to allow field-testing at the biodigester facility at SATS. The construction permit applications for the engine and NOx emission control device were submitted to the Sacramento Municipal Air Quality Management District (SMAQMD) in July

2015. The SMAQMD issued the construction permit to CleanWorld effective June 2, 2016. Table 1 presents the emission standards issued by SMAQMD.

Table 1: Emission Standards

Pollutant	Emission Standard and Work Practice
NO _x	11 ppmvd corrected to 15% oxygen
CO	250 ppmvd corrected to 15% oxygen
VOC	0.1 g/hp-hr
H ₂ S	40 ppmvd fuel gas influent
Ammonia	11 ppmvd corrected to 15% oxygen

CHAPTER 2:

Project Approach

The criteria for the field demonstration of pre- and postcombustion NO_x control were developed after the CHA Corporation had a meeting with CleanWorld. Then, the engineering drawings were prepared and major equipment items were identified. Equipment items and fabricated microwave reactors and heaters were purchased based on the major equipment list. CHA had all microwave generators and exhaust gas heat exchangers from previous field testing.

CHA built a container that housed all equipment for the microwave steam reforming for the pre-combustion NO_x control. After the container was transported and installed at the CleanWorld SATS BioDigester Facility, CHA installed equipment for the post-combustion NO_x control. Then, piping for biogas and engine exhaust was installed.

2.1 Engineering Design and Fabrication Drawings (Task 2)

CleanWorld intended to maximize its production of natural gas from the biogas and to use about 30 cfm biogas for the engine. The biogas consisted of about 67% CH₄ and 33% CO₂. A detailed design basis that included the maximum operating capabilities, temperature, and pressure was developed based on this information. Then, the process flow diagram (PFD) and material balance table were prepared.

2.1.1 Process Flow Diagram

Figure 2 presents the (PFD) for field-testing of the pre- and postcombustion NO_x Control for the biogas engine with microwave energy. This NO_x control system consists of pre-combustion NO_x control and postcombustion NO_x control. These two NO_x control systems operate either independently or combined.

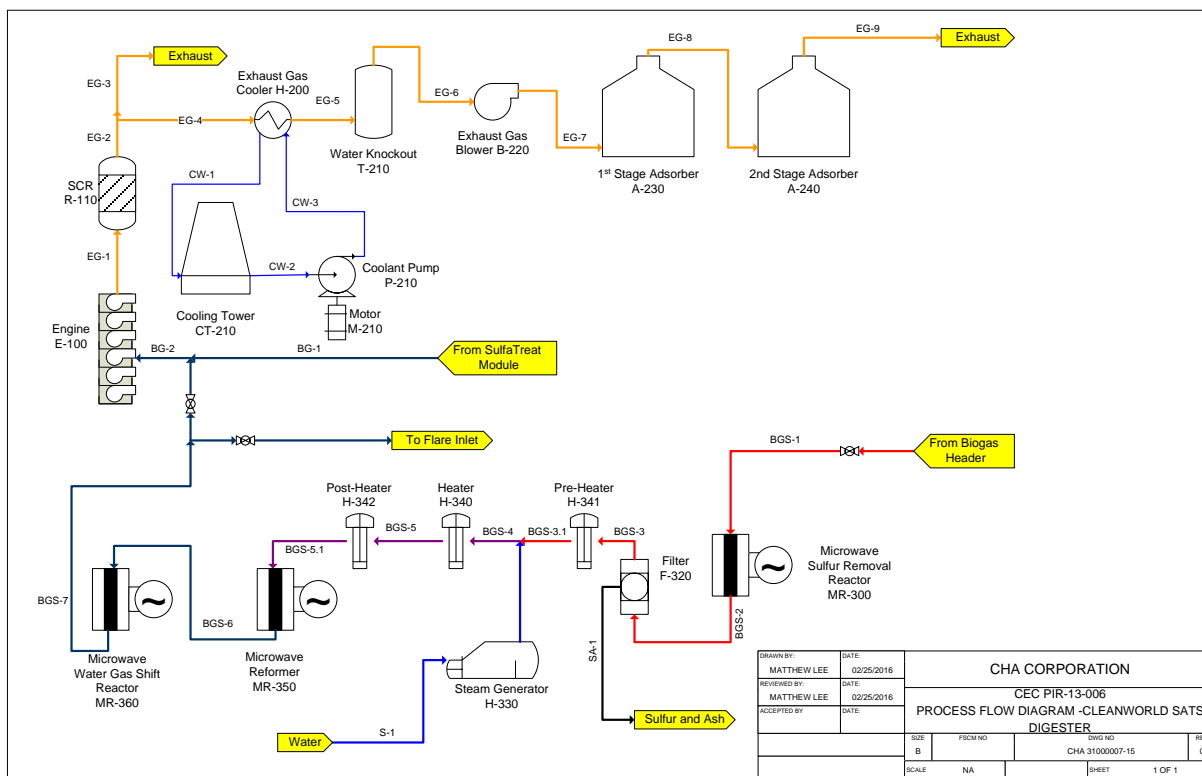
The pre-combustion NO_x control system consists of microwave-GAC reactor MR-300 for H₂S removal, microwave reactor for steam reforming MR-350, and microwave reactor for Water Gas Shift MR-360. A side stream of biogas from the inlet to carbon filter of the bio-CNG system or CNG after the separator could be used as feed gas for H₂ generation.

The biogas or CNG enters the MR-300 to remove and destroy H₂S and other sulfur impurities. The filter F-320 captures the elemental sulfur contained in the outlet gas from the MR-300. The sulfur free biogas or CNG is heated in the pre-heater H-341 and then mixed with steam. The mixture of biogas and steam enters heater H-340 and post-heater H-342 to be heated to about 900-1,000°F (482.2-537.8°C). Then, the heated mixture of steam and biogas or CNG enters the steam reformer MR-350 to convert CH₄ into H₂, CO, and CO₂. The gas leaving the reformer MR-350 flows into the water gas shift reactor MR-360 to convert CO into H₂ and CO₂. Hydrogen and other gases leaving the MR-360 are combined with engine inlet biogas and flow into the engine.

The postcombustion NO_x control system consists of the water-cooled exhaust gas cooler H-200 to cool exhaust to about 100-150°F (37.8-65.6°C), water knockout T-210, exhaust blower B-220,

first stage adsorber A-230 and second stage adsorber A-240. The B-220 withdraws the exhaust gas from the inlet to the stack and supplies the cooled exhaust gas to A-230 and A-240 to remove NO_x. There is a heat exchanger in the 190-kW engine exhaust line after the SCR R-110. This heat exchanger is not connected to the digester heating system, however it could be connected to the digester boiler system but was not used during the field-testing. The exhaust gas is withdrawn from the engine exhaust system at the inlet to the stack. The exhaust gas from the stack flows into the H-200 and then T-210. Cooled exhaust from the T-210 enters the A-230 of the two-stage NO_x removal adsorber unit. The exhaust gas leaving the A-240 is discharged into the atmosphere. When the average NO_x concentration from the A-240 exceeds 5-ppm at 15% O₂ concentration, the saturated GAC is reactivated in the A-230. The adsorber filled with reactivated GAC is operated as the second stage adsorber A-240. The SO₂ and VOC in the exhaust were removed by GAC in the adsorber. The inlet and outlet gas of A-230 and A-240 will be monitored continuously to calculate the amount of NO_x removed from the exhaust and the time-average NO_x emission that is defined as cumulative NO_x emitted into atmosphere divided by cumulative adsorption time.

Figure 2: Process Flow Diagram



2.1.2 Process Piping and Instrumentation Diagram

Process piping and instrumentation diagrams (P&ID) were prepared using the PFD and design basis. Figures 3 through 6 present P&ID for the pre-combustion NO_x control system that were developed based on the PFD in Figure 2. A Programmable Logic Controller (PLC) controls the pre-combustion NO_x control.

Figure 3 shows the P&ID of the microwave reactor MR-300 for H₂S removal. A side stream of biogas is taken from the inlet to carbon filter of bio-CNG system. Also, a side stream of CNG after carbon filter could be taken for H₂ production if biogas has CH₄ concentration lower than 65%. The pressure of this biogas is high enough to pass the mixture of biogas and steam through the steam reforming system. The pressure regulator PRV-002 will reduce the biogas pressure to 15 pounds per square inch gauge (psig). The pressure indicator PI-003 shows the inlet biogas pressure. The mass flow controller QC-004 controls the biogas flow rate to MR-300, which receives the control signal from the PLC. This mass flow controller was malfunctioned and was replaced with the rotameter. The sample valve SL-302 provides gas samples from the inlet of the MR-300.

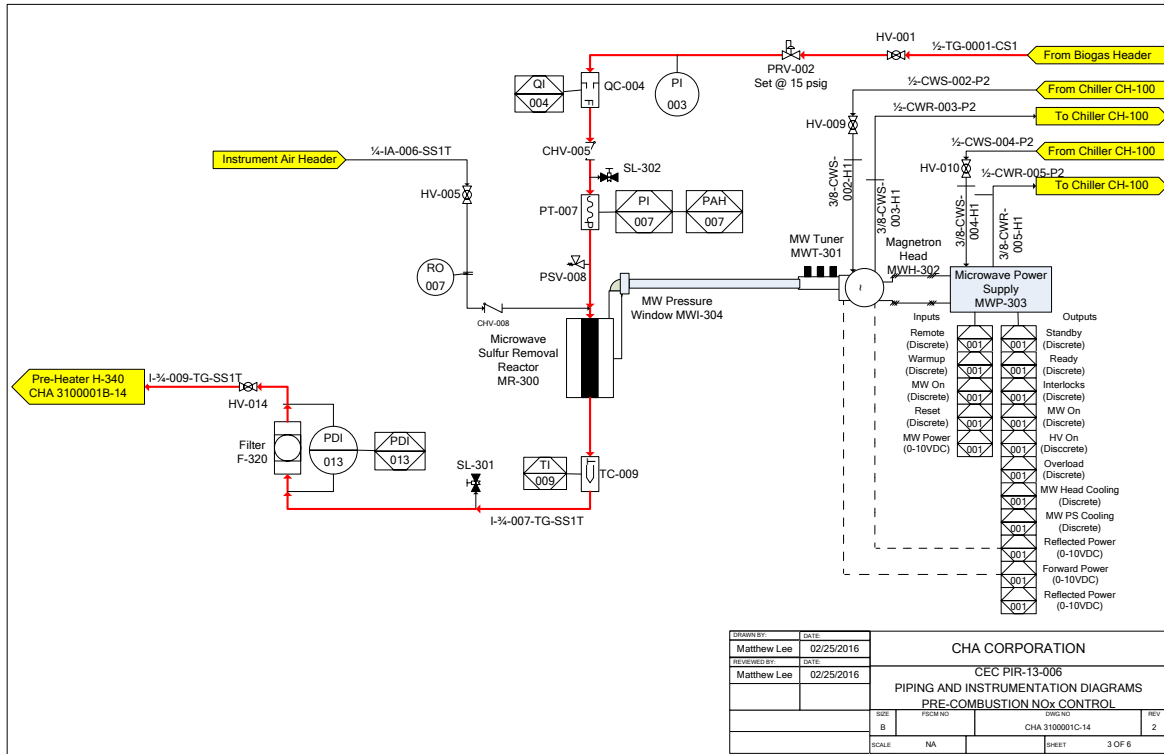
The thermocouple TC-009 measures the temperature of biogas leaving MR-300 that is shown in TI-009. The Sample Valve SL-301 provides the sample of the MR-300 outlet gas. The gas leaving the filter F-320 enters the preheater H-341.

The MR-300 is connected to microwave tuner MWT-301 and magnetron head MWH-302. The microwave power supply MWP-303 supplies power to the MWH-303 that generates microwave power (3 kW) for MR-300. The microwave generator is equipped with numerous internal interlocks, any one of which will trigger a fault signal to stop the microwave generator. The reflected power is measured through an N-type coaxial port and is displayed on the power supply MWP-303. The MWT-301 controls the reflected power manually. Chiller CH-100 supplies cooling water to MWH-302 and MWP-303.

Figure 4 shows the P&ID for the microwave reformer MR-350 system. The biogas from the F-320 enters the preheater H-341. The heated gas from the H-341 is combined with steam and enters the main gas heater H-340. The thermocouple TC-3301 measures the temperature of gas leaving the H-341.

The critical orifice FO-023 is used to measure the steam flow rate. The pressure change across FO-023 is measured by the differential pressure transmitter PDI-023, which is sent to the PLC to calculate the rate of steam flow. The steam flow control valve FCV-023 receives a signal from the PLC and controls the steam flow rate. The boiler feed pump P-331 supplies water to the steam generator H-330. The check valve CHV-020 prevents steam flow to P-331 and CHV-024 prevents the flow of biogas to Steam Generator H-330.

Figure 3: P&ID for Microwave H2S Removal Reactor



The main gas heater H-340, preheater H-341, and postheater H-342, are controlled by the PLC. The thermocouple TC-3401 measures temperature of the gas leaving H-340. To increase the temperature of gas entering the microwave reformer MR-350, the heat tap defined as H-342 and controlled by the PLC, was installed around the inlet to MR-350. The thermocouple 3501 measures the gas temperature at the H-342 outlet, which is the inlet to MR-350.

The MR-350 is connected to microwave tuner MWT-351 and magnetron head MWH-352. The microwave power supply MWP-353 supplies power to MWH-353 that generates microwave power (6kW) for the MR-350. The microwave generator is equipped with numerous internal interlocks, any one of which will trigger a fault signal to stop microwave generator. The reflected power is measured through an N-type coaxial port. MWT-351 controls the reflected power manually. The CH-100 supplies cooling water to MWH-352 but MWP-353 is cooled by air.

The diagram illustrates the piping and instrumentation for a pre-combustion NOx control system. Key components and their connections are as follows:

- Water Supply:** Water enters from the bottom left (3/8-011-W-CS1) and is pumped by the Boiler Feed Pump (P-331) to the Steam Generator (H-330) via line HV-019.
- Steam Generation:** The Steam Generator (H-330) produces steam, which is controlled by a Steam Valve (SV-021) and a Control Valve (CHV-020). The steam is then directed to the Microwave Reformer (MR-350) via line HV-025.
- Reformer and Heating:** The Microwave Reformer (MR-350) is powered by a Microwave Power Supply (MWP-353) and a Magnetron Head (MWH-352). The reformer's output is heated by a Post-Heater (H-342) and a Pre-Heater (H-341). The heaters are controlled by Temperature Controllers (TC-3501, TC-3401) and Temperature Indicators (TI-3502, TI-3402, TI-3304).
- Gas Flow and Control:** The gas flow is monitored by a Flow Transmitter (FT-023) and a Flow Indicator (FI-023). The flow is controlled by a Flow Controller (FCV-023) and a Flow Orifice (FO-023). The gas is then directed to the WGS Reactor (MR-360) via line 1/2-012-S-CS1.
- Instrumentation:** The system includes various sensors and actuators, including Pressure Indicators (PDI-023, PDT-023), Pressure Transmitters (P-023), and Control Valves (CHV-024, CHV-018, CHV-020).
- Chiller and Cooling:** The system is cooled by a Chiller (CH-100) via line 1/2-030-CWS-P2. The chiller is controlled by a Chiller Water Temperature (CWT-351) and a Chiller Water Pressure (CWP-354).

The diagram is titled "CHA CORPORATION CEC PIR-13-006 PIPING AND INSTRUMENTATION DIAGRAMS PRE-COMBUSTION NOx CONTROL".

The MR-360 is connected to microwave tuner MWT-361 and magnetron head MWH-362. The microwave power supply MWP-363 supplies power to the MWH-363 that generates microwave power (3 kW) for MR-360. The microwave generator is equipped with numerous internal interlocks, any one of which will trigger a fault signal to stop microwave generator. The reflected power is measured through an N-type coaxial port and is displayed on the MWP-363. MWT-361 controls the reflected power manually. The CH-100 supplies cooling water to MWH-362 and MWP-363. The chiller CH-100 supplies the cooling water to three microwave generators. Figure 6 shows the P&ID for the CH-100.

Figure 5: P&ID for Microwave Water Gas Shift Reactor

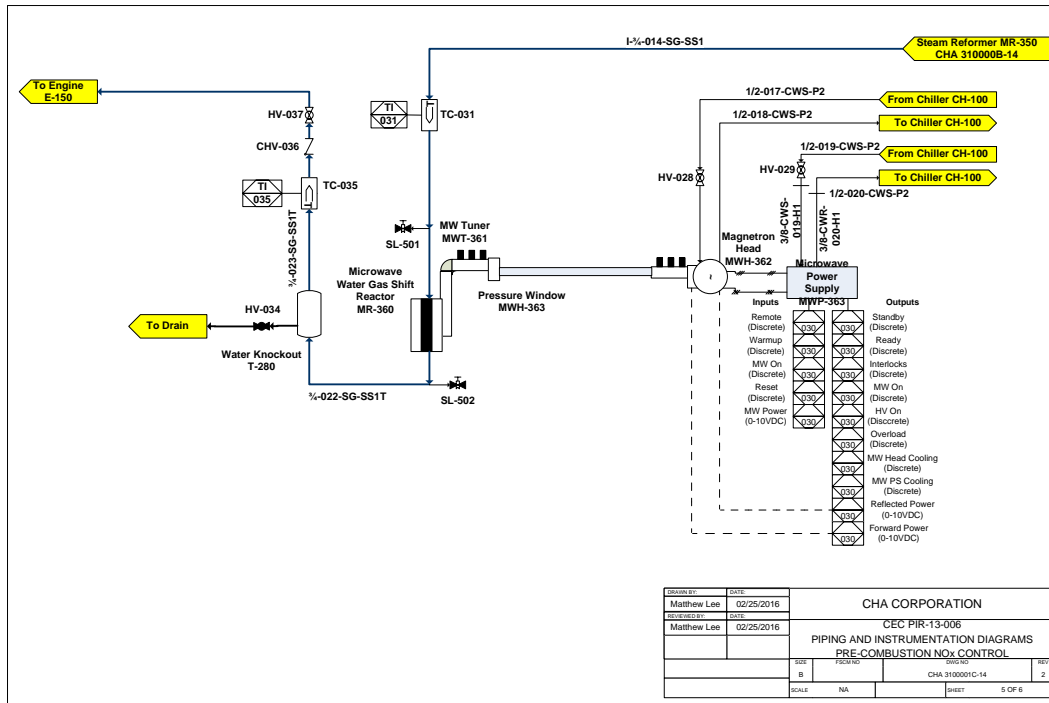


Figure 6: P&ID for Chiller for Microwave Generators

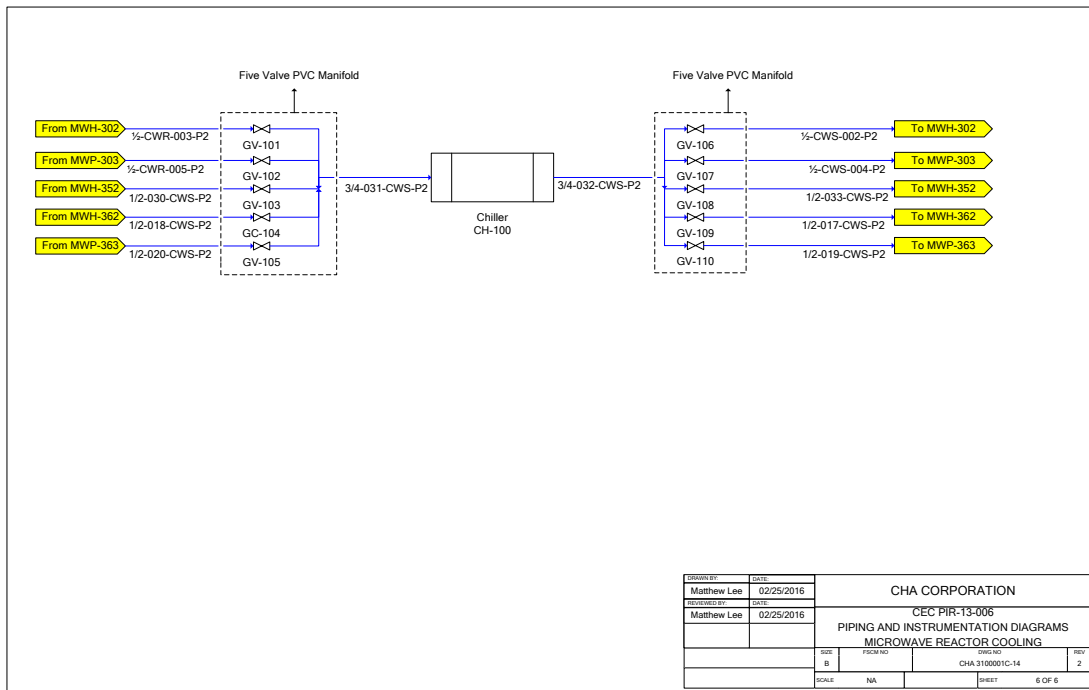
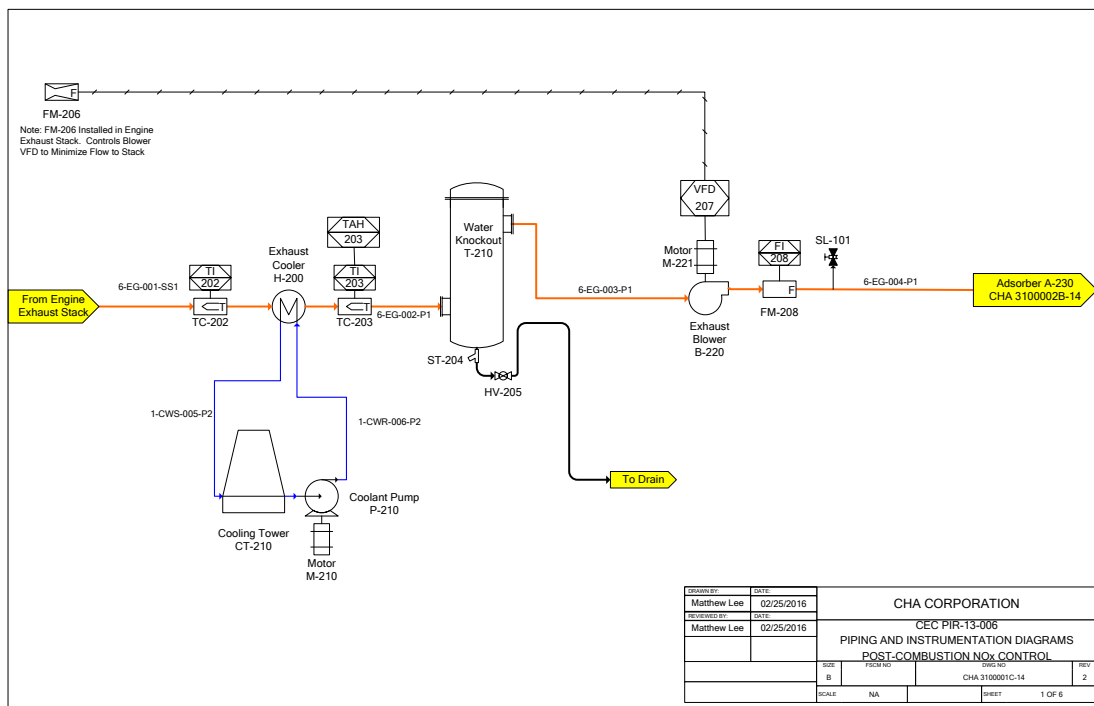


Figure 7 presents the P&ID of the exhaust gas cooler system for the post-combustion NOx control system. The exhaust gas blower B-220 supplies the gas to the adsorber A-230 or A-240 at the constant flow rate set by the variable speed Motor M-231. The flow meter FM-208 measures the exhaust gas flow rate to the adsorber A-230 or A-240. Since the exhaust gas flow rate was calculated using the biogas flow rate and exhaust O₂ concentration, this flow meter FM-208 was eliminated to reduce project expenses. The exhaust O₂ concentration was measured by the NOx monitor every 30 minutes.

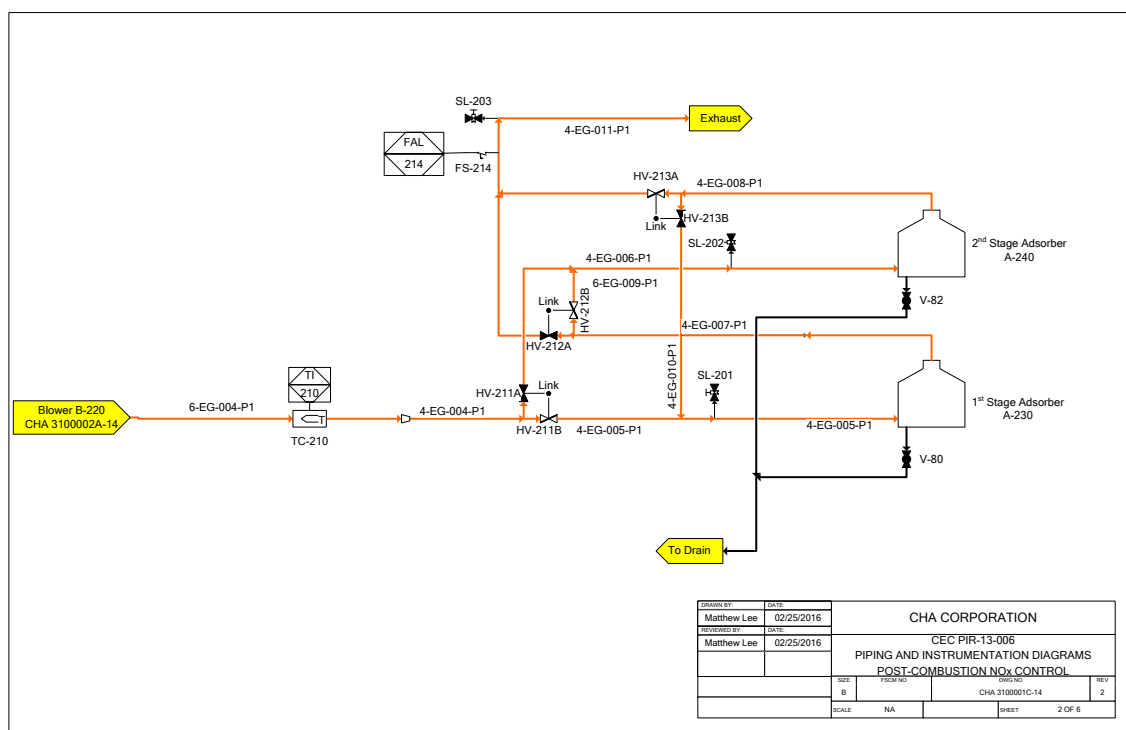
Figure 7: P&ID for Exhaust Gas Cooler and Water Knockout



The exhaust gas cooler H-200 is a water-cooled heat exchanger and reduces the exhaust gas temperature to about 120°F (48.9°C). The cooling tower CT-210 supplies cooling water to H-200. The coolant pump P-210 circulates water through the CT-210 and H-200 to cool exhaust gas. The sample valve SL-102 provides the sample of exhaust gas. The O₂ and NOx concentrations of inlet gas to the first adsorber A-230 will be measured by connecting the combustion gas meter to SL-102.

Figure 8 show the P&ID for the activated carbon adsorber A-230 and A-240. Sample valves SL-201 and SL-202 provide the exhaust gas samples from the inlet and outlet of the first stage Adsorber A-230. The SL-203 provides exhaust gas sample from the second stage adsorber A-240

Figure 8: P&ID for two-stage Activated Carbon Adsorbers



The major equipment list was prepared based on PFD and process piping and instrumentation diagrams.

2.2 Procurement of Equipment and Materials (Task 3)

2.2.1 Procurement of Equipment and Materials

Microwave reactors for the removal of H_2S , steam reforming, and water gas shift were built and used for the previous project. Materials to upgrade these three microwave reactors were purchased. Inlet and outlet flanges were refabricated to reduce gas leaks. These microwave reactors were tested in the lab steam reforming tests to verify operational performance. Wave guides from Gerling Engineering to connect microwave reactors to microwave generators were purchased. The research team installed these microwave reactors and generators inside the equipment container for field-testing.

CHA purchased the main body of the high-temperature gas heater and heating element to build the heater. CHA also purchased a used steam generator that was much cheaper than new steam generator. A new steam flow control valve and a boiler feed pump with motor were purchased.

CHA has a 20-ft shipping container that was used to accommodate pre-combustion NOx control equipment for field testing at the CleanWorld Biodigester site. Circuit breakers, wires, electric supplies, and parts for installing process units inside the container were purchased. The container was transported from storage to the CHA lab and cleaned up. The door and the steel floor to locate the equipment items were installed. The steel floor was welded to the container

floor and wall. The air conditioner was installed and the container was painted. Equipment items including control panel, steam generator, and microwave generators were located. To isolate the electric cabinet and microwave power supply cabinet from the microwave reactors, the interior wall was installed inside the container. Microwave reactors and gas heaters were mounted close to the door separated by the wall. The power supply cabinet, microwave generators, steam generator, air conditioner, and electrical cabinet were located in the other side of the container.

The cooling water requirement for three microwave generators was calculated and the specification of the chiller was determined. A used chiller was purchased in Santa Rosa, California. With minor repairs, the chiller operated without any problems. For the exhaust gas cooler, the heat removal requirement was estimated, and a 25 nominal ton cooling tower was purchased from RSD in California. Because of limited space, the cooling tower was located at the top of the container. The supporting structure at the top of the container was built to hold the cooling tower.

A PLC was purchased from the automation direct. The PLC software for controlling the 6-kW microwave power supply, the steam flow, and biogas flow rate was prepared and tested. The heater controls have been written in two versions, proportional integral and derivatives (PID) and on/off control. After these two versions were tested, the PID control was selected over the simple on/off control. Two 3 kW microwave power supplies were controlled manually.

Two G-5 adsorbers were purchased from Carbtrol Corp and delivered in June 2016. These adsorbers are steel tanks with a bottom dump gate for carbon removal. Each adsorber has a capacity of 2,000 lbs. of carbon and has forklift fittings for handling. This adsorber could be moved by the front loader to the mobile microwave reactivation unit located for the reactivation of used carbon.

The researchers found OXPURE™ 4W-100 extruded activated carbon. This 4 mm GAC is produced from wood through a thermal acid activation process and has the carbon tetrachloride (CTC) number of 100. Because of the high CTC number, this carbon was expected to have higher NO_x adsorption capacity than CTC-80 GAC. Also, this carbon was cheaper than CTC-80 GAC. Because of higher CTC number and lower price, OXPURE 4W-100 was chosen for the post-combustion NO_x control. Based on the NO_x adsorption data obtained from previous field-testing at Tollenaar Dairy, Elk Grove, California under the ICAT project, NO_x emissions were expected to be maintained under 5-ppm with one adsorber filled with 2,000 lbs. of GAC without pre-combustion NO_x control if it is reactivated monthly.

The blower used in the previous project can handle 300-500 cfm gas flow. This blower was used to withdraw the engine exhaust gas for the post-combustion NO_x control system. The pressure of biogas from the Bio-CNG carbon filter is high enough for the steam reforming system. As a result, neither the exhaust gas blower nor the biogas compressor was purchased.

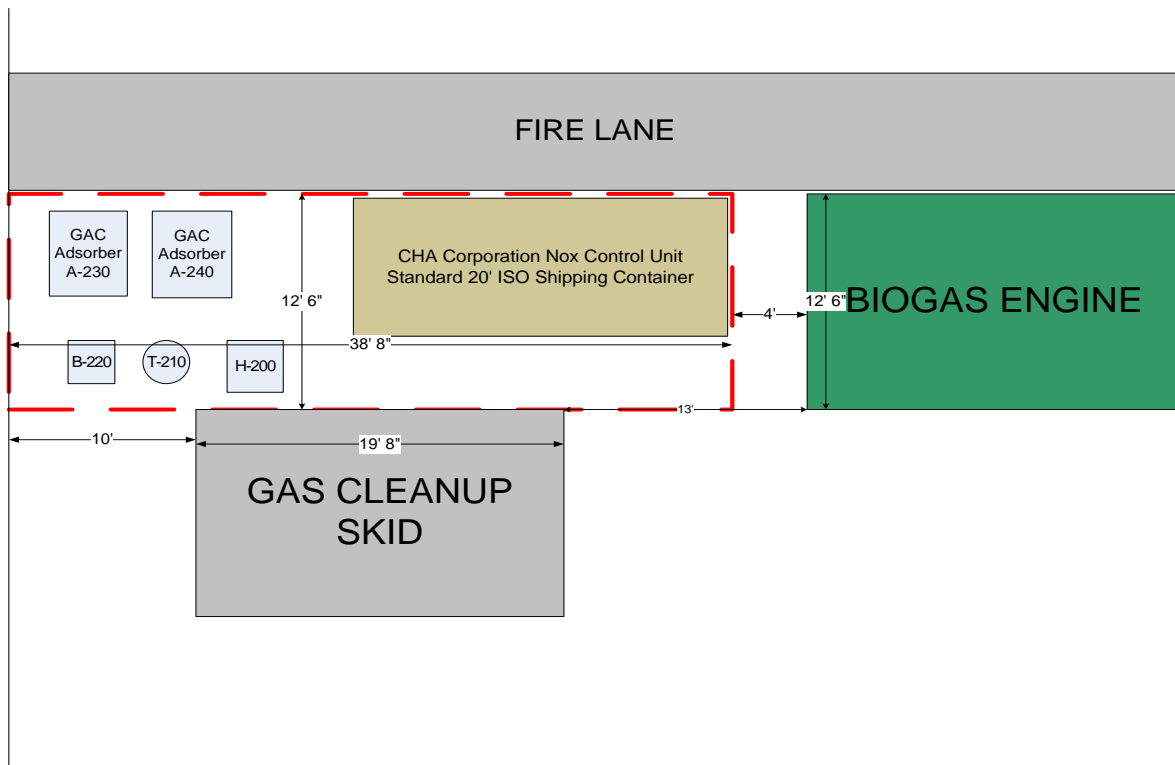
2.2.2 Site Inspection

CHA staff toured the CleanWorld BioDigester site on March 29, 2016. Upon arriving at the BioDigester site, the operating area and plumbing connections were assessed, and possible connections with staff were discussed. The following was determined:

- Water is readily available for use in the CHA cooling tower and steam generator.
- Any produced water such as condensed water and blowing out from steam generator would be collected and discharged to the sewer. No used and produced water would be discharged onto the ground. CHA set up a water collection tank and they set up the sump pump to divert water to the sewer.
- Due to low pressure of biogas inside digesters (0.5 psi), CHA could draw biogas from the compressor outlet of the Bio-CNG carbon filter for steam reforming and H₂S removal test. The pressure of this biogas is about 100 psig and the pressure regulator reduced this pressure to about 10 psig for steam reforming. Other biogas lines could be accessed if needed.
- Due to safety concerns, major electrical equipment should be setup at least 8 feet away from any biogas or natural gas connection.
- To provide adequate hydrogen feed to the engine, a larger connection was tapped into the air intake. The current 1/8" connection was too small. Adams of CleanWorld and CHA staff could handle this installation.
- Engine exhaust for the post-combustion NO_x control test could be drawn from the 8" pipe flange leading to the exhaust stack.
- An unused pipe was connected to the flare, which was used by CHA to burn the hydrogen produced in the steam reforming if the engine was not running.

Figure 9 shows the site layout for the field-testing of pre- and post-combustion NO_x control system.

Figure 9: Site Layout



2.3 Fabrication of Process Units (Task 4)

2.3.1 Fabrication of Process Units

CHA did not use the machine shop to build any process units. Microwave reactors used for previous ICAT projects were modified and repaired for the microwave steam reforming system. Furthermore, mailbox microwave applicators and flanges used for previous projects were also repaired. The main process unit fabricated was the main gas heater.

Based on the fabrication drawings developed under Task 2, the heater body and heating element were assembled and the main gas heater was built. This heater was used for microwave reforming lab testing. The heater was controlled by the PLC. In addition to this main heater, another gas heater was constructed using heat tape because the heating rate of main heater was too slow and provided only about 800°F (426.7°C) of inlet gas to the steam reformer.

The steam generator was assembled and connected to transmitter, micro-connector, and steam trap for the steam generation. The steam flow control valve was tested and calibrated.

The heat exchanger and blower used for the previous ICAT project was repaired for the post-combustion NOx control system. The water knockout pot was fabricated and constructed.

2.3.2 Laboratory Test Plan

The laboratory test plan was prepared to determine the operating parameters for field testing of the integrated NO_x control system. Natural gas and CO₂ were used to simulate the biogas. To minimize the use of NG, a 1.5 cm quartz tube was placed inside a 7.6 cm quartz tube. The main objective of the H₂S removal lab test was to determine the effect of superficial gas velocity and microwave power on H₂S removal and destruction efficiency. The superficial gas velocities tested were 18-41 cm/s.

CleanWorld recovers about 40 cfm bio-CNG from 100 cfm biogas. The 60 cfm of remaining biogas is produced as tail gas that is burned in the flare. The tail gas consists of 33% CH₄ and 67% CO₂ with trace nitrogen. If tail gas is used in the field testing successfully, this tail gas could be an excellent candidate for a fuel cell that may generate power for bio-CNG production. Thus, the lab steam reforming test plan was prepared using simulated tail gas.

The first objective of the steam reforming lab testing was to find the maximum tail gas flow rate that produces 2.8 cfm H₂ with CH₄ conversion greater than 70%. It was also necessary to find the minimum steam/CH₄ ratio that provides CH₄ conversion greater than 70%.

The simulated tail gas contained 67% CO₂ and 33% NG. The tail gas passed through the H₂S removal reactor that was packed with GAC. The microwave energy enhances the reaction of CO₂ with carbon to produce CO. The produced CO reacted with steam to produce H₂ and CO₂ in the water gas shift reactor. As a result, it was desirable to maximize this reaction to reduce the tail gas flow rate for providing 10% H₂ in the engine inlet biogas.

The second objective for laboratory test was to evaluate the performance of the three microwave reactors (H₂S removal, steam reforming, and water gas shift reactor) that would be used for steam reforming during the field-testing of the pre-combustion NO_x control system. These three microwave reactors were installed on the rack for lab testing. The H₂S removal and water gas shift reactors were equipped with 3 kW microwave generators. The steam reformer was equipped with a 6 kW microwave generator. In addition, an electric steam generator and gas preheater were operated and the performance of these components were evaluated.

Since the H₂S removal tests using CTC-70 and CTC-80 GAC were completed, H₂S was not added to the simulated tail gas for lab testing. In the previous lab testing, it was demonstrated that the H₂S in the simulated biogas was completely removed with 300 W and superficial gas velocity of 41 cm/s. The H₂S removal reactor for the field test ran at 3 kW and, it was expected H₂S in the tail gas could be decomposed completely. The tail gas has about 10 ppm H₂S. For lab testing, the H₂S removal reactor was operated at 3 kW to decompose the 3-4 ppm sulfur components in NG to prevent poisoning the steam-reforming catalyst.

Following is a list of specific objectives for laboratory steam reforming tests.

- Measure the conversion of CO₂ to CO in the H₂S removal reactor.
- Investigate the effect of the steam/CH₄ ratio on the CH₄ conversion.
- Investigate the effect of tail gas flow rate on the conversion of CH₄ to H₂.

- Determine the highest tail gas flow rate and the minimum steam/CH₄ ratio that gives a CH₄ conversion to H₂ greater than 70%.
- Determine tail gas and steam flow rates that provide 8-10% H₂ in 30 cfm biogas inlet to engine.
- Determine the field-testing operational parameters.
- Conduct a long-term test using the field-testing operational parameters.

After installing the lab testing system, the shakedown test was started using the simulated biogas consisting of 67% NG and 33% CO₂. The 28 L/min of NG flow rate is the same as CH₄ in 3 cfm tail gas. The steam/NG ratio for the shakedown test was 2.5, which is 25% greater than the stoichiometric ratio. Also, the shakedown test data were used to evaluate the effect of CO₂ concentration on the CH₄ conversion.

The first series of tests were to find the CH₄ or NG conversions at four steam/NG ratios. The tail gas flow rate of 3 cfm (85 L/min) would be used for the first series of tests. The 3 cfm tail gas would provide about 8% H₂ in the biogas to an engine running on 30 cfm. Superficial gas velocity for the tests was 27-44 cm/s.

The results from the first series of tests would determine the effect of steam/NG ratio on the conversion of CH₄ in the tail gas. To increase H₂ production rate, it would be necessary to increase the tail gas flow rate for steam reforming. Increasing the steam/CH₄ ratio increases the conversion but also increases the total gas flow rate, which decreases the conversion. Therefore, there should be the optimum NG and steam flow rates for CH₄ conversion to meet the required H₂ production rate. The next series of reforming tests were to determine the effect of tail gas flow rate or superficial gas velocity on CH₄ conversion.

2.4 Assembly and Testing of the Precombustion NOx Control System (Task 5)

2.4.1 Assembly of the Microwave Steam Reforming System for Lab Testing

The microwave steam reforming system was installed in the lab to finalize the steam reforming system design for field testing precombustion NOx control. The main challenge was to heat the inlet steam and gas to about 1,000°F (537.8°C). The gas preheater was built using the refractory wall. Because it took a long time to heat refractory, the previous gas preheater was installed to heat gas into the main gas heater. With two heaters in series the mixture of NG and CO₂ combined with steam was heated to 650°F (343.3°C) after one hour. To control the heating rate of the refractory, the control system for the inlet gas preheater was constructed. Also, a gas preheater using heating tape was connected to the main PLC to control heating rate. Four heating options were tested to find the optimum heating arrangement to increase the inlet gas temperature to about 1,000°F (537.8°C). A gas preheater was used to heat NG and CO₂ and the main gas heater was used to heat the mixture of gas and steam. Then, the heater outlet gas was heated by heat tape installed around the pipe from the heater to the reformer. This arrangement provided reformer inlet gas at a temperature higher than 1,000°F (537.8°C). In

addition, a steam control valve was installed to inject steam to the water gas shift reactor. This finalized the reformer design for pre-combustion NO_x control. Figure 10 shows the steam reforming system for the lab testing.

Figure 10: Microwave Steam Reforming System



2.4.2 Laboratory Test Result

The steam-reforming test was started with simulated tail gas by mixing NG with CO₂. The tail gas produced by the CleanWorld BioDigester consists of 33.3% CH₄ and 66.7% CO₂. The hydrogen required for precombustion NO_x control of the engine running on 30-cfm biogas is about 80 L/min or 85 L/min tail gas with 70% conversion. The steam reforming test was started with 42 L/min simulated tail gas (14 L/min NG and 28 L/min CO₂) with 2.5 kg/h steam and measured the CH₄ conversion and H₂ production rate. The CH₄ conversion at 42 L/min tail gas was 57%, which was much lower than expected. The CH₄ conversion was 70% at 30 L/min tail gas and decreased to 55% as the gas flow rate increased to 54 L/min.

The H₂ production was 33 L/min at 30 L/min tail gas flow and increased to 44 L/min as tail gas flow increased to 54 L/min. This result clearly indicated that tail gas could not be used to

supply H_2 required for pre-combustion NO_x control. Consequently, CHA decided to use biogas instead of tail gas for the steam reforming test. The CH_4 conversion was much more dependent on the flow rate than expected.

Because of low CH_4 conversion the original lab test plan for steam reforming was not conducted and all steam-reforming tests were conducted using simulated biogas.

Biogas contains twice as much CH_4 than as tail gas at the same flow rate. Mixing two-third of NG and one-third of CO_2 simulated the biogas. The steam reforming test was started at 30 L/min simulated biogas (20 L/min NG and 10 L/min CO_2). Test results are presented in Figures 11 and 12 for various simulated biogas flow rates.

Figure 11: Methane Conversion vs. Simulated Biogas Flow Rate Without Additional Steam

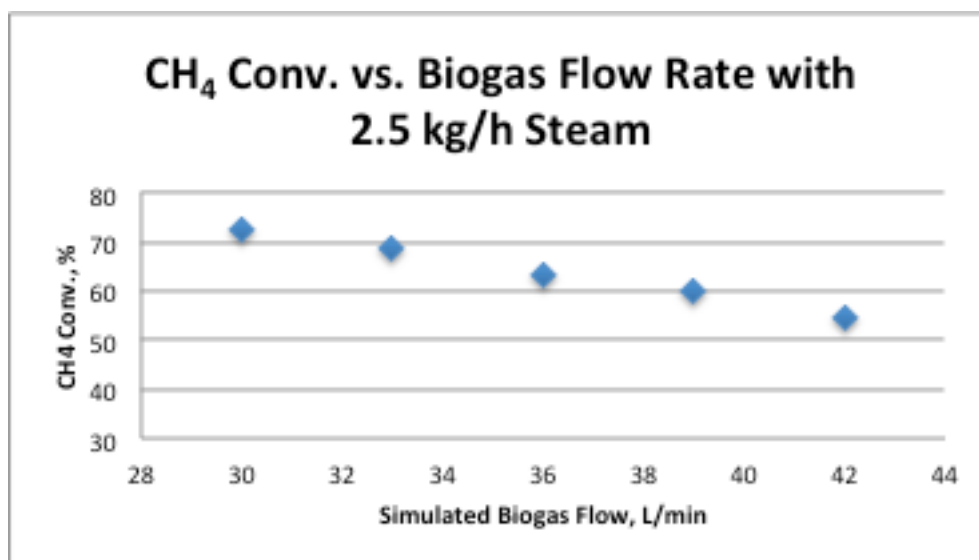
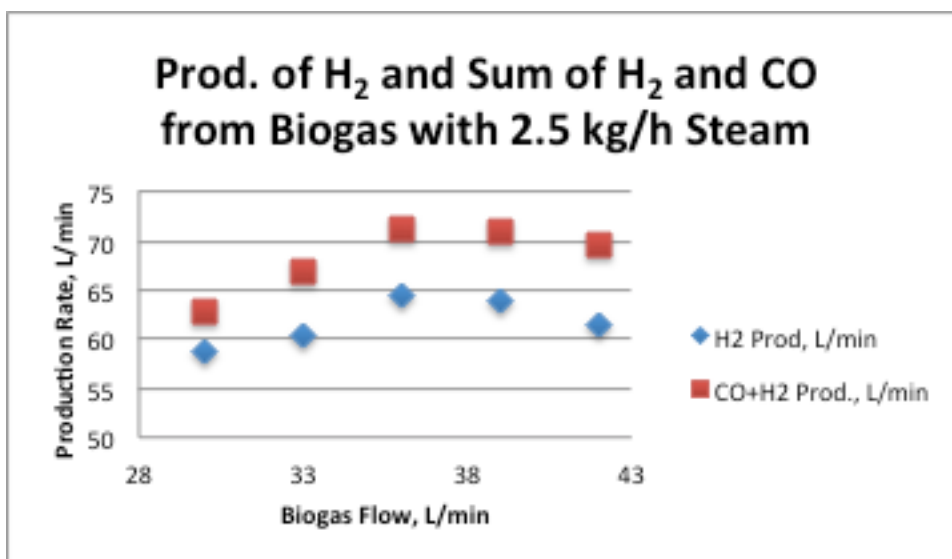


Figure 12: H_2 Production vs. Biogas Flow Rate Without Additional Steam



The CH_4 conversion was 73% at 30 L/min simulated biogas with 2.5 kg/h steam but decreased to 54% as the flow rate increased to 42 L/min. The H_2 production rate was 59 L/min at 30- L/min simulated biogas and increased to 64 L/min H_2 at 39 L/min biogas. Then, the H_2 production rate decreased to 62 L/min as the biogas flow rate increased to 42 L/min. Because of a too high inlet gas flow rate to the reforming reactor, the steam flow rate was reduced from 3 kg/h to 2.5 kg/h and did not increase as the biogas flow increased. The CO production was 7 L/min at 39 L/min simulated biogas and additional injection of steam to the water gas shift reactor would increase H_2 production to 71 L/min.

A steam control valve was installed to inject steam into the water gas shift reactor. Then, reforming tests were repeated. The results from additional steam injection are presented in Figures 13 and 14.

Figure 13: Methane Conversion with Additional Steam Injection

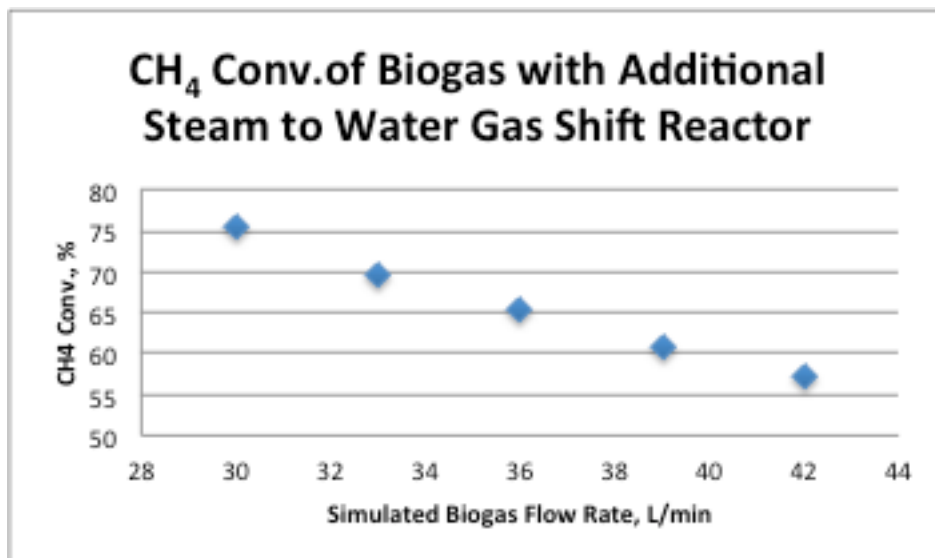
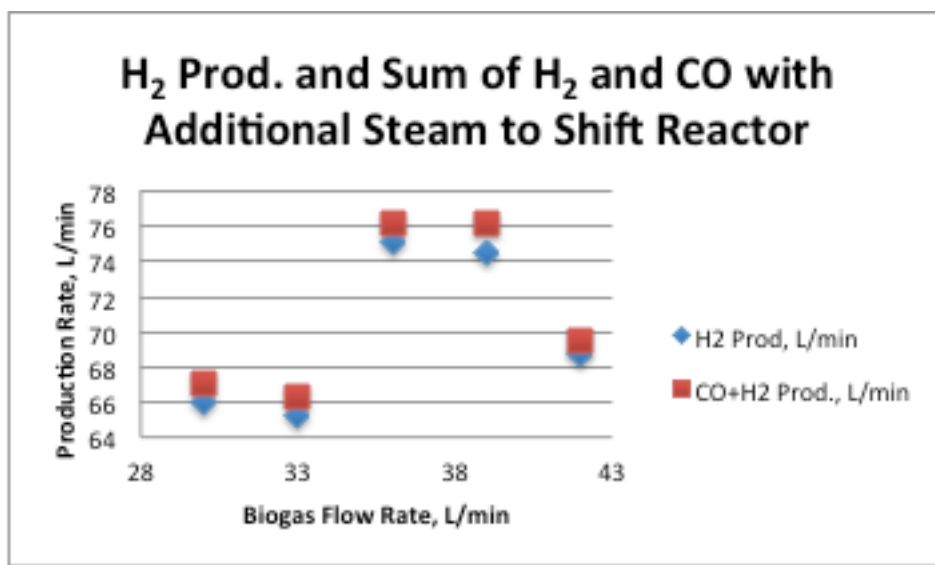


Figure 14: H₂ Production with Additional Steam Injection



With additional steam injection to the water gas shift reactor, the CH₄ conversion increased by 2% and H₂ production increased by 10 L/min as shown in Figures 13 and 14. Also, CO production was reduced to 1 L/min. Hydrogen production was 75 L/min when the simulated biogas was in the range of 36 to 39 L/min. This indicated that slight improvement of CH₄ conversion could produce 80 L/min H₂ for pre-combustion NO_x control.

The target inlet gas temperature from gas preheater was 1,000°F (537.8°C); however, only 800°F (426.7°C) was achieved. Increasing inlet gas temperature will increase CH₄ conversion. Researchers traced the steam line with heat tape to increase the temperature of inlet steam to the gas heater to increase inlet gas temperature. Heat taping the inlet steam line increased the temperature of the heater outlet gas by about 40°F (4.4°C) but the CH₄ conversion did not increase.

Researchers removed the heat tape from the inlet steam line and installed heat tape around heater outlet pipe before the reformer. Installing the heat tape around the reformer inlet pipe increased temperature of reformer inlet gas faster and higher. The inlet gas temperature increased to 1,000°F (537.8°C) after 90 minutes. The results from this series of tests are presented in Figures 15 and 16. Increasing inlet gas temperature to 1,000°F (537.8°C) increased the CH₄ conversion significantly, especially at higher gas flow rates. The conversion at 39 L/min simulated biogas was increased from 61% to 70%. Also, the conversion at 42 L/min was increased from 57% to 65%. The H₂ production was also increased. The H₂ production of 75 L/min was the highest at the highest biogas flow of 42 L/min that was used in these series of tests. It is not clear if the H₂ production would increase further if biogas flow increases. This possibility would be investigated during the field-testing. The CO production was 1.5 L/min, which indicates that increasing steam flow to the water gas shift reactor would increase H₂ production.

Figure 15: Methane Conversion With Heat Tape Installed Around Reformer Inlet Pipe

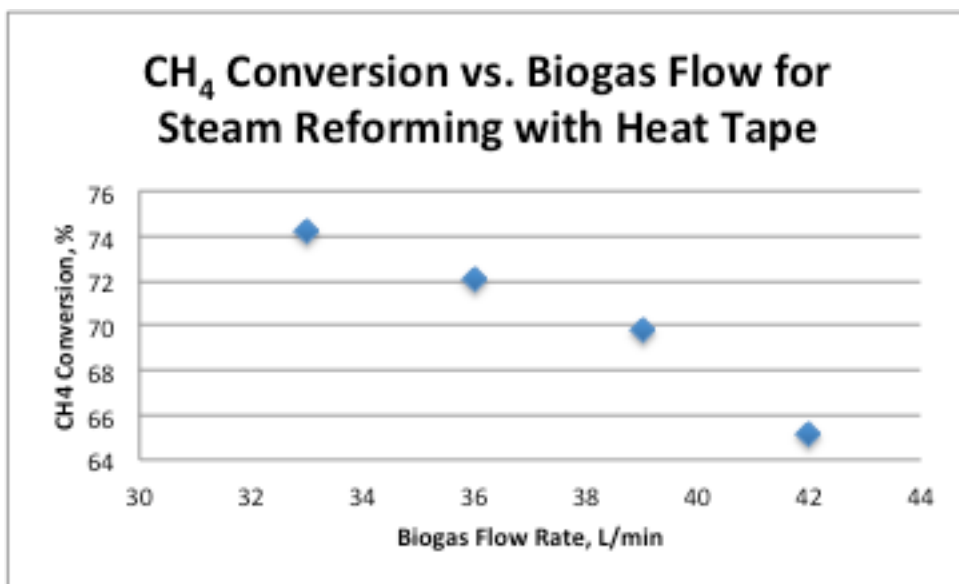


Figure 16: Hydrogen Production With Heat Tape Installed Around Inlet Pipe

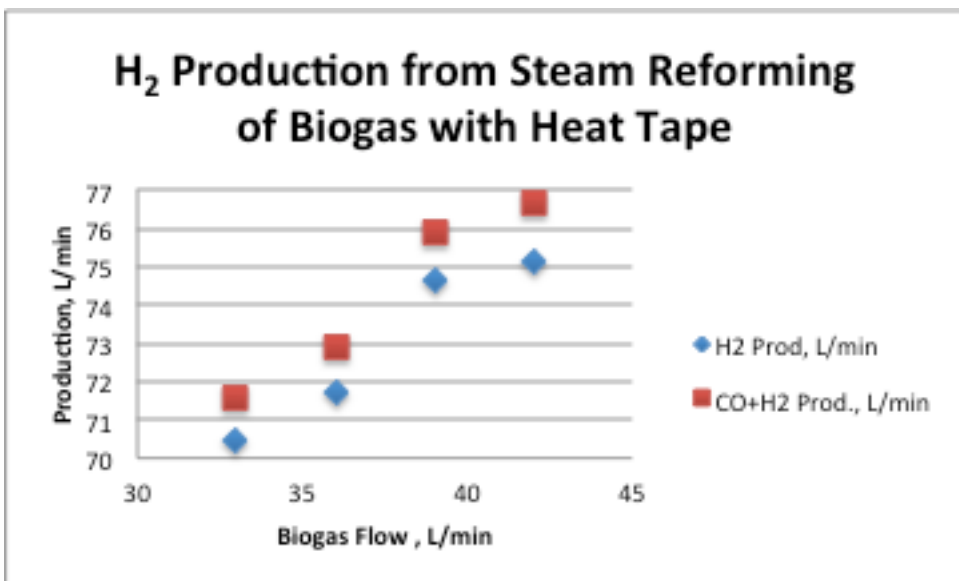


Table 2 presents the composition of gas from steam reforming tests. The H₂ concentration decreased as the biogas flow increased due to the decrease in the CH₄ conversion.

Table 2: Composition of Gas from Steam Reforming Lab Tests

Simulated Biogas, L/min	33	36	39	42
H ₂ , %	68.1	66.6	65.9	64.2
CH ₄ , %	5.4	6.2	6.9	8.3
CO, %	1.1	1.2	1.1	1.3
CO ₂ , %	25.4	26	26.1	26.2

The 75 L/min H₂ generation from steam reforming of biogas will provide 8.8% H₂ in the inlet gas to the engine running on 30-cfm biogas. This may provide sufficient H₂ concentration to reduce NO_x emission. The HALO was tested only for natural gas. Oxides of nitrogen emissions of 10-ppm were obtained using 8% H₂ supplementing an exhaust oxygen level of 10%. Because HALO has not been tested for the biogas-powered engine, the proper H₂ supplementation level for NO_x emission control is not known. The biogas contains 30-40% CO₂ that may act as the excess air and H₂ supplementation level could be lower than 8%.

Since the heat tape installed around the heater outlet pipe increased inlet gas temperature to 1,000°F (537.8°C) or higher, the preheater will be relocated to heat CO₂ and NG entering the H₂S removal reactor, R1. The CO₂ conversion by reacting with carbon in R1 reactor was 9% at one cfm and 1.5% at 2 cfm of the simulated biogas when gas was preheated to 800°F (426.7°C). Since biogas to the R1 reactor will be lower than 1.5 cfm for the field test, CO generated in R1 reactor could be more than 2 L/min. With increase in the steam to the water gas shift reactor, CO produced from CO₂-C reaction could increase H₂ production to 80 L/min for pre-combustion NO_x control. The 80 L/min of H₂ would increase H₂ supplementation to 9.4% in the inlet gas to the engine running on 30 cfm biogas.

After the steam reforming tests were completed, the reforming catalyst was removed to see if carbon black was generated and accumulated. About 323g of carbon were separated from catalyst. This indicated that some of NG was cracked because of insufficient steam flow into the reformer. Because of too high of a gas flow rate, steam flow was reduced from 3 kg/h to 2.5 kg/h, which increased the CH₄ conversion more than 1%. Most of the reforming tests were conducted using 2.5 kg/h steam. For tests with NG greater than 24 L/min the ratio of steam to NG was lower than stoichiometric ratio of 2 if the reforming reaction produces H₂ and CO₂. To minimize NG cracking steam higher than 2.5 kg/h should be used.

To investigate the possibility for minimizing NG cracking, the steam reformer was packed with catalyst again and the researchers conducted more tests with higher steam flow rates. Also, the steam was introduced during the preheating and after the NG flow was discontinued upon completion of the test to remove carbon generated from CH₄ cracking. To investigate the effects of steam flow, a series of tests were conducted using 20 L/min NG and 10 L/min CO₂ with various rates of steam. Figure 17 presents the CH₄ conversions at various steam flow rates. The CH₄ conversion to H₂ was 81% at 2.5 kg/h steam flow and increased to 83% as the steam

increased to 3.0 kg/h. Then, the conversion decreased to 81% when steam increased to 4.0 kg/h. The 3.0 kg/h steam flow was the optional steam flow rate for 20 L/min NG and 10 L/min CO₂.

Figure 17: Methane Conversion as a Function of Steam Flow

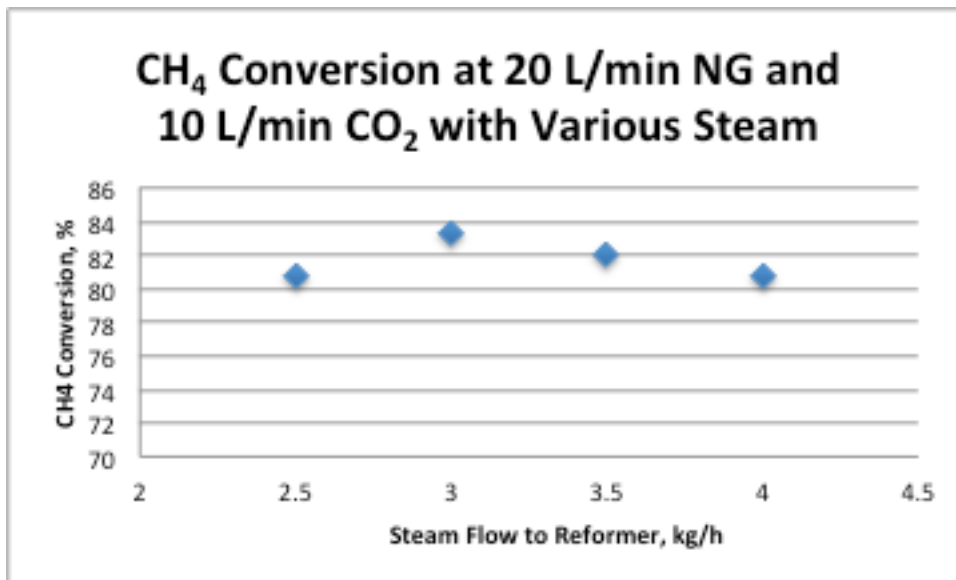
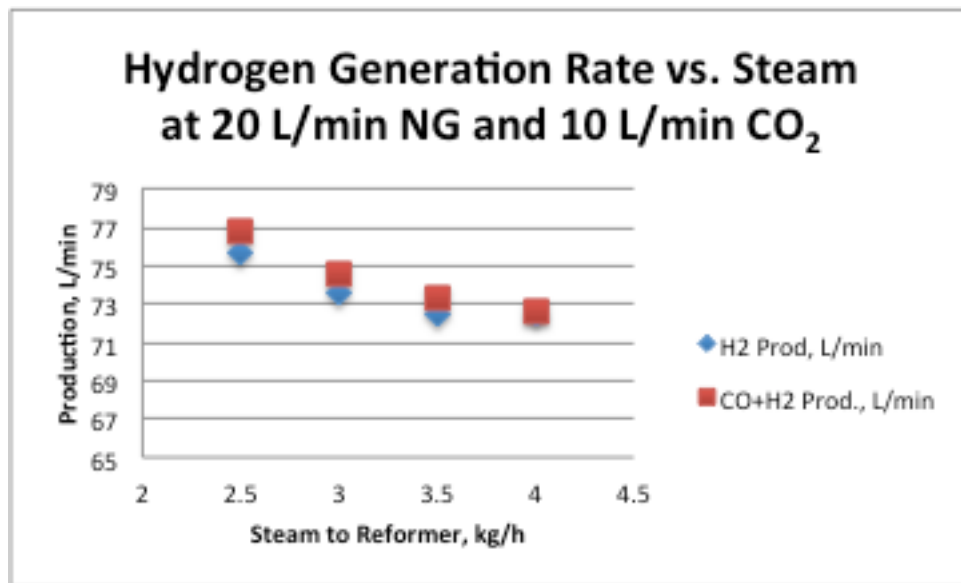


Figure 18 presents H₂ production rate at various steam flow rates using 20 L/min NG and 10 L/min CO₂. This figure shows that the H₂ production rate decreased as the steam flow increased. It is not clear why H₂ production decreased as the steam flow increased. The outlet gas flow rate was calculated using carbon balance. If NG cracking produces carbon, the carbon balance would not be accurate for calculating the outlet gas flow rate. This may be one of reasons why lower steam flow yields higher H₂ production. Because of high temperature combined with high moisture content, it is very difficult to measure the flow rate of dry outlet gas from the water gas shift reactor.

Figure 18: Hydrogen Production as a Function of Steam Flow



2.5 Installation of Pre- and Post-Combustion NO_x Control System at CleanWorld BioDigester at SATS (Task 6)

2.5.1 Equipment Container

All steam reforming equipment to produce hydrogen from biogas for pre-combustion NO_x control was installed inside a 20-ft shipping container. Also, the power control panel and sampling valves for the post-combustion NO_x control were installed inside the container. The container housing all equipment for the pre-combustion NO_x control was transported to the CleanWorld BioDigester site at the SATS located at 8550 Fruitridge Road, Sacramento, California. The container was next to the 190-kW biogas-powered engine container.

CleanWorld's electrical subcontractor installed the electric power supply line from the main power cabinet to the container. The 480 V electric power supply is connected to the electric disconnect in the container power panel. Three microwave generators and main gas heater use 480V electric power. The transformer in the container converts 480 V to 208 V for the steam generator, air conditioner, chiller, cooling tower, and exhaust gas blower. The transformer also converts 480 V to 110 V for instruments, fan, and lights.

Figure 19 shows the picture of the container and post-combustion NO_x control system located close to engine container (left side).

Figure 19: Picture of Container and PostCombustion NOx Control System



2.5.2 Pre-Combustion NOx Control

Figure 20 shows the picture of the container that houses the precombustion NOx control system. Piping was installed to a tap into CleanWorld's BioCNG compressor outlet pipe before the GAC filter to supply biogas to the H_2S removal reactor and steam reformer. The piping was also installed from the water gas shift reactor to the water knockout and then the engine inlet. To bypass the hydrogen and other steam reforming product gas, piping was installed between the water gas shift reactor and flare. If the engine is not running, the reformer product gas will flow into the flare.

Figure 20: Container and Heat Exchanger



2.5.3 Post-Combustion NOx Control

The post-combustion NOx control system consists of the exhaust gas blower, heat exchanger and cooling tower to cool exhaust, and two GAC adsorbers. This equipment was placed outside the container. The dimension of the adsorber is 48-inch x 48- inch x 75-inch high and each adsorber holds 2,000 pounds of GAC. These adsorbers were located outside the container and installed in series (Figure 19).

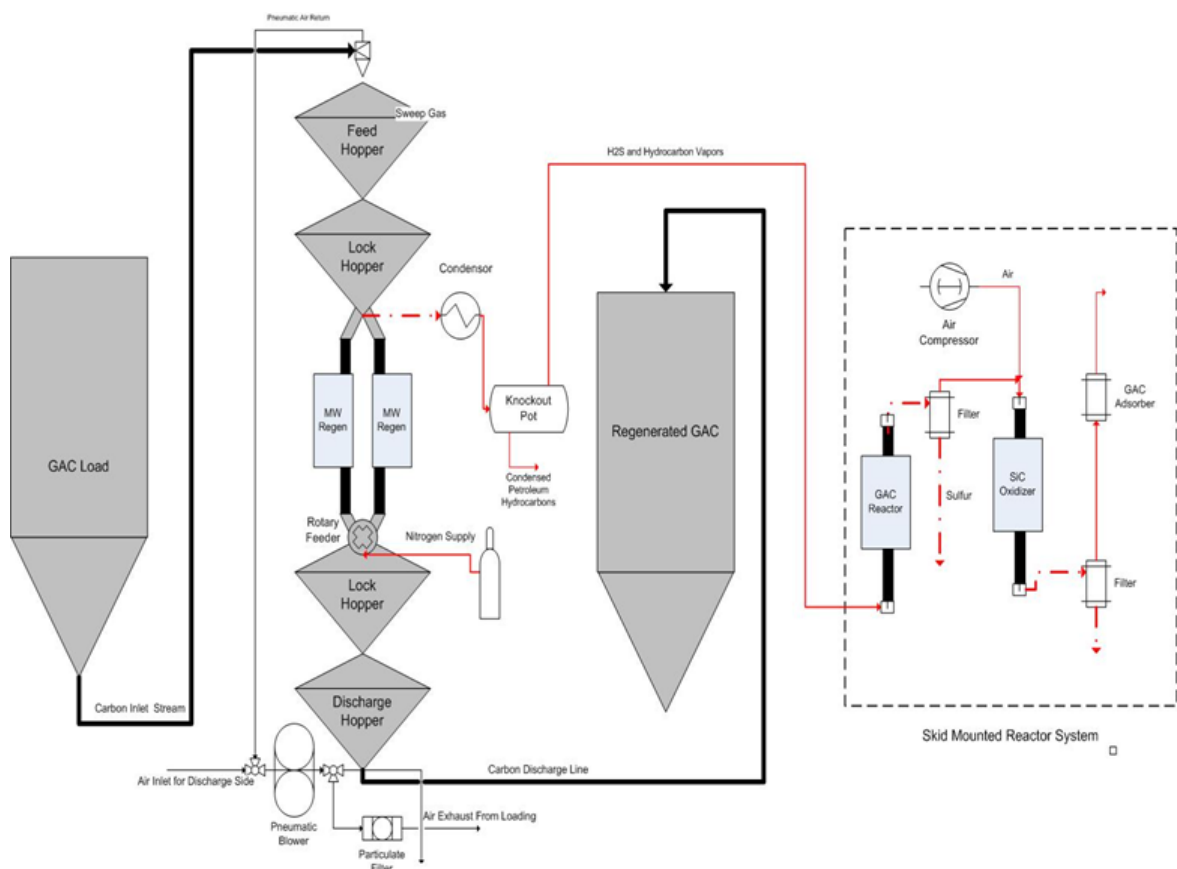
Piping was installed to connect the exhaust blower and heat exchanger to the first-stage adsorber for the postcombustion NOx control. Then, piping was installed from the engine stack inlet to the heat exchanger, blower and two GAC adsorbers. Piping was also installed from the

cooling tower to the heat exchanger. Because of limited space, the cooling tower was installed at the top of the container.

2.5.4 Mobile Microwave Reactivation Unit

CHA has a mobile microwave reactivation unit. The mobile microwave reactivating unit uses two 6 kW quartz microwave reactors to process carbon at an overall rate of 100-lb/h. One of the 6 kW power supplies was not working and needed to be repaired by the manufacturer. One of two microwave reactors was removed and the capacity of the reactivator was reduced to 50-lb/h. Figure 21 presents the PFD of the microwave carbon reactivation process.

Figure 21: Process Flow Diagram for Microwave Carbon Reactivation Process



The carbon hoppers are arranged in an airlock configuration, to allow continuous processing of activated carbon. After the top feed hopper is filled, a knife-gate valve on the top is closed. Then the hopper is purged with N_2 to remove the O_2 from hopper. After the hopper is purged, a knife-gate valve between two feed hoppers opens, dumping the purged carbon into lower feed hopper. The knife-gate valve then closes, and the load-and purge-cycle is repeated until the saturation carbon hopper or adsorber is emptied.

The flow of carbon through each quartz tube is controlled by the motor speed of the star valve. There is enough adjustment in the star valve speed to set the carbon throughput between 10 and 120-lb/h. The rotary valve design has been significantly improved over previous systems.

The size of the rotor was increased and the carbon inlet was offset from the centerline. These modifications reduce carbon attrition in the feeder by decreasing the number of rotor revolutions at a given feed rate, and decrease the occurrence of carbon bridging in the quartz tube by increasing the depth of the pocket where carbon enters the feeder.

The carbon from the feed hopper is processed through the microwave reactor. The reactor consists of a quartz tube that is connected to the hoppers by an O-ring seal. The quartz tubes pass through aluminum microwave cavity applicators, where the microwaves are applied. The carbon flows by gravity through the quartz tubes, and into the top product hopper. At the bottom of each reactor is a rotary feed valve that is driven by a variable speed direct current (DC) motor.

The same airlock principle used for feed hoppers is used for product hoppers. The carbon from the reactor fills the top product hopper and opening a knife-gate valve allows the hopper to empty into lower product hopper. The carbon is held in the lower product hopper until cool, and then transferred by the conveyor belt into the receiving container.

To remove and condense the desorbed NO_x and hydrocarbons, a sweep gas is passed countercurrent to the carbon stream. The carbon entering the quartz tube passes through an adapter that contains a stainless-steel screen. The side of the adapter has a port where the vapor is drawn from carbon and enters the condensers.

The gas is then chilled in the condenser, which is a pair of double pipe heat exchangers. These were chosen after additional testing of the unit at McClellan Park indicated that processing carbon loaded with chlorinated solvents produced an acidic condensate. To accommodate this, the inner tubes of the heat exchangers that encounter vapor are thin walled Teflon tubes. The coolant is a water-propylene glycol mixture and cooled by the chiller that is used for microwave generators. The cooled gas and condensed liquid passes through the condenser into the knockout pot. The liquid drops into this tank, while the gas passes onto the microwave de-NO_x reactor.

The microwave De-NO_x reactor is filled with GAC that reacts with NO_x to produce N₂ and CO₂. Also, H₂S and SO₂ react with carbon to produce the elemental sulfur, water vapor and CO₂. The GAC reactor outlet gas passes through the filter to capture elemental sulfur. Then, it combines with about 1 cfm air and flows into the microwave oxidizer that is filled with silicon carbide (SiC). The hydrocarbons contained in the reactivation gas are oxidized by air. The GAC used for upgrading biogas generated from landfill and wastewater treatment contains siloxanes. The reactivation gas will contain siloxanes, which will be oxidized to produce silicon oxide (SiO₂) that will be removed by the filter. Finally, the gas flowing through the SiO₂ filter will emit into the atmosphere after passing through the GAC adsorber to capture any remaining pollutants.

To accommodate the physical constraints of the system, the unit was designed as a skid mounted system that was loaded on a trailer. The reactor system was mounted in an erectable derrick that could be elevated via a hydraulic system. The derrick is raised and lowered hydraulically, and will slide forward on the trailer to ease transport. The trailer was modified with outriggers at the front and the back to support the load. The derrick is fixed to the end of

the main skid. The main skid supports the control room, refrigeration system, knockout tanks, piping, and wiring. Figure 22 shows this mobile microwave reactivation unit.

The mobile microwave unit was relocated to CleanWorld BioDigester site at SATS. This unit was used to reactivate NO_x-saturated GAC. In addition, CleanWorld may require this microwave reactivator to reactivate saturated GAC on hand and GAC filter used for removing H₂S and nonmethane hydrocarbons including VOCs.

Figure 22: Mobile Microwave Reactivation Unit



2.6 Field Testing of the Pre-and Post Combustion NO_x Control (Task 7)

The goal of the field testing was to demonstrate that the combination of the microwave-based pre- and post-combustion NO_x control could meet the Rule 1110.2 and CARB 2007 NO_x emission standards. The field testing was to achieve several goals: 1) H₂S concentration of microwave treated biogas less than 0.1 ppm; 2) a biomethane conversion greater than 70% 3) NO_x concentration reduction by H₂ injection greater than 70%; 4) NO_x emission less than 5 ppm; and 5) SO₂ and VOC removal more than 90%.

After the field testing system was installed, researchers conducted the post-installation tests to ensure that all microwave reactors and other units operate properly. Shakedown tests of the system startup, normal operation, and shutdown procedures were conducted to determine proper operating conditions.

2.6.1 Field Testing of Pre-Combustion NOx Control

The field-testing of the pre-combustion NOx control system consisted of three parts; (1) H₂S removal, (2) steam reforming of biogas, and (3) air/fuel ratio control for NOx reduction. The biogas was taken from the carbon filter of CNG system and contained about 67% CH₄ and 33% CO₂.

The goal for the microwave H₂S removal testing was to demonstrate that the microwave-GAC reactor would completely remove and decompose H₂S in biogas for steam reforming to prevent sulfur poisoning of the nickel catalyst. The biogas is a promising candidate for producing H₂ for fuel cell. To evaluate the feasibility of the microwave-GAC reactor, the H₂S removal efficiency will be obtained as a function of biogas flow rate at 3kW microwave power.

H₂S removal is much more effective with a trace amount of air since microwave energy catalyzes the reaction of H₂S with oxygen in the GAC reactor to produce steam and elemental sulfur. This reaction is exothermic and requires very low microwave power. The biogas may contain 0-2% of oxygen. If the biogas does not contain a trace of oxygen, a small amount of air will be added to the biogas to increase the effectiveness of microwave-induced H₂S removal. The H₂S concentration of treated biogas was measured with and without adding air.

During lab testing the H₂S removal tests were also conducted with higher superficial gas velocities at 200-ppm inlet H₂S concentration with 300W. The superficial gas velocity increased from 53 to 107 cm/s. No H₂S was detected in outlet gas from the microwave GAC reactor. Even when the inlet H₂S concentration increased to 1,800-ppm, H₂S was destroyed with 300 W at 107 cm/s superficial gas velocity. The research team conducted the H₂S testing to confirm this result with biogas from the Bio-CNG filter.

The lab testing showed that the tail gas could not produce H₂ required for the pre-combustion NOx control. The biogas from the Bio-CNG GAC compressor outlet was used for the steam reforming test. The main objective of the steam reforming test was to find out if the biogas could produce the H₂ required for pre-combustion NOx control with the conversion efficiency greater than 70%.

After the H₂S removal field testing was complete, the steam-reforming test began using the biogas without operating the engine. The slipstream of biogas from the inlet to GAC filter at the Bio-CNG system was used and the reformed gas flowed to the flare. The main objective of this initial reforming test was to confirm the result obtained from the lab testing and establish the steady state H₂ generation for the pre-combustion NOx control. The CH₄ conversion efficiency of biogas was obtained at various ratios of steam to CH₄ and biogas flow rates that were selected from lab testing. The team determined the maximum biogas flow rate and minimum ratio of steam to CH₄ that provide the CH₄ conversion efficiency were greater than 70%. From the initial steam reforming tests of biogas, the operating parameter for pre-combustion NOx control for the engine running on 30-cfm biogas would be determined. With selected biogas and steam flow rates, the steady state long-term H₂ production test was conducted for at least one week before starting the pre-combustion NOx control test.

Because of low CH₄ concentration of biogas and the operational problems of the bio-CNG system, the steam reforming testing was run using the CNG tank. The CH₄ conversion efficiency and H₂ production rate were determined from microwave reforming of CNG.

After the steady state steam reforming test, the engine operated with 30 cfm biogas combined with H₂ from steam reforming of biogas for two weeks to obtain the NOx emission data without changing the air/fuel ratio. The NOx emissions from two GAC beds were monitored to see the effect of H₂ injection without changing the air/fuel ratio.

The main goal of the pre-combustion NOx control was to field-test the HALO technology combined with microwave system for onsite H₂ production. With previous stable engine operation without adding H₂, the A/F ratio and NOx emission were obtained as the basis for the pre-combustion NOx control test. Because CleanWorld did not have the authority from 2G to control the air/fuel ratio, it was not possible to run the engine without the engine specialist authorized by 2G.

When the pre-combustion NOx control test was conducted, the engine specialist from Western Energy ran the engine with air/fuel ratio greater than 1.4. Because of the low CH₄ content of biogas, the engine ran for about five hours for three days of precombustion testing. The engine experienced operational problems and CHA could not continue the pre-combustion NOx control test. However, the NOx emission data were obtained with higher air/fuel ratios.

2.6.2 Post-Combustion NOx Control Field Test

The goal of the integrated system of pre- and post-combustion NOx control was to meet the Rule 1110.2 (average NOx emission of 11-ppm) soon and ultimately meet CARB 2007 standards (average 5-ppm NOx emission). To investigate the feasibility of using the post-combustion NOx control without pre-combustion NOx control, the SCR was bypassed. The SCR will not reduce NOx without reducing agent, urea. The engine exhaust bypassed the SCR without injecting urea to SCR during the post-combustion NOx control testing.

CHA submitted the applications for engine and NOx emission control device to SMAQMD. The NOx emission control device consists of SCR and two GAC adsorbers. If the NOx emission from SCR is greater than 11-ppm, the GAC adsorbers could be operated with SCR to meet the NOx emission standards.

Since Clean World had not conducted the SCR performance test, the NOx removal efficiency by SCR was measured before the post-combustion NOx control test. The SCR had many operational problems including the urea injection system. The exhaust gas temperature should be greater than 600°F (315.6°C) to achieve good performance of SCR. As a result, the engine ran at its full capacity for the SCR performance evaluation. The NOx concentrations were measured at the inlet and outlet of the SCR during urea injection. The O₂ concentration of exhaust gas was measured to convert NOx emission at 15% O₂ concentration. If the NOx emission at 15% O₂ concentration is lower than 11 ppm, the SCR will meet the NOx emission standards.

After NOx emission data for the evaluation of SCR was obtained, the SCR did not operate throughout the field testing by not injecting the urea. The biogas flow to the engine was reduced to about 30 cfm for the field testing.

Before changing the air/fuel ratio, CHA conducted the postcombustion NOx control test for two months without precombustion NOx control. The NOx emission from the first and second stage GAC beds were measured hourly during the postcombustion NOx control tests. Then the amount of NOx adsorbed by the first-stage GAC bed and by the second stage GAC bed was calculated. The daily average NOx emission from the second-stage GAC bed was measured.

CHA researchers started the postcombustion NOx control test with one adsorber filled with fresh GAC. When the average NOx concentration of the single adsorber outlet gas reached 5-ppm at 15% O₂ concentration, a second stage adsorber was added. The average NOx concentration of the outlet gas from the second stage adsorber was also be monitored continually. When the average NOx emission from the second stage adsorber reached 5 ppm at 15% O₂ concentration, the first stage adsorber was disconnected. This adsorber was transported to the microwave reactivation unit and the saturated GAC was reactivated. When the GAC was reactivated, the adsorber was filled with the reactivated GAC and placed as a second stage adsorber. The goal was to replace the SCR with activated carbon adsorbers for postcombustion NOx control.

The SCR installed at the engine is not equipped with the oxidation catalyst. The air permits require the removal of VOCs. The construction applications include two activated carbon beds that will remove VOCs in exhaust. The operating permit may require for CleanWorld to keep the carbon adsorber for operating engine.

2.7 Estimating System Capital and Operating Costs (Task 8)

The goal of this task was to determine from the project findings that the pre- and postcombustion NOx control with microwave energy process could be a cost-effective NOx control method for biogas-powered engines to meet the CARB 2007 emission standards.

Based on field test results, CHA developed the (PFD) for a 500-kW biogas powered IC engine. Using this PFD and the major equipment list developed under Task 2, a major equipment list with purchasing price for the pre- and postcombustion NOx control system was prepared. Then CHA estimated the capital cost for installing the pre- and postcombustion NOx control system.

Using field test results, the annual operating cost of the pre- and postcombustion NOx control system were estimated. The amount of NOx removed from the engine exhaust and the NOx removal cost per ton of NOx removed was also estimated. The NOx removal cost by the microwave-based integrated system were compared with the conventional SCR NOx control system.

Because of low capital cost and the simplicity, the capital and operating costs for the postcombustion NOx control using two carbon adsorbers in series were estimated. It was assumed that the saturated carbon will be reactivated at the central microwave reactivation facility.

NOx-saturated carbon was reactivated in the mobile microwave reactivation unit that was relocated to the SATS BioDigester site. Because of high O&M cost for replacing the GAC, the capital and O&M costs for the integrated post-combustion NOx control with onsite microwave reactivation were estimated.

Based on biogas steam reforming test results, the applicability of the microwave hydrogen production system for fuel cells was evaluated. The microwave H₂S removal for biogas cleanup was also evaluated.

2.8 Decommissioning of Field Demonstration System (Task 9)

The goal of this task was to remove all equipment items installed at the CleanWorld BioDigester Facility so that the engine site could be returned to normal.

CHA removed the piping that was installed to a tap in CleanWorld's Bio-CNG compressor outlet pipe prior to the GAC filter to supply biogas to the H₂S removal reactor and steam reformer. The piping that was installed from the water gas shift reactor to the water knockout and then the engine inlet was also removed. To bypass the hydrogen and other steam reforming product gas, piping was installed between the water gas shift reactor and flare. This piping was removed. Thus, the equipment container is ready to be removed from the field testing site if the cooling tower at the top is removed.

The post-combustion NOx control system consisted of the exhaust gas blower, heat exchanger and cooling tower to cool exhaust, and two GAC adsorbers. This equipment is placed outside the container.

Two adsorbers were transported to the microwave reactivation mobile unit located at CleanWorld's SATS digester site. Saturated GAC in these two beds were reactivated. Then two adsorbers were filled with reactivated GAC and transported back to the original location. These adsorbers are ready to be used to remove NOx from the engine exhaust. CHA proposed Glenbrooks for the reactivation of saturated GAC generated from the carbon filter of Bio-CNG system and NOx removal. The mobile microwave reactivation unit will stay at the digester site until Glenbrooks makes the decision on CHA's proposal.

The Sacramento Metropolitan Air Quality Management District issued the construction permit to CleanWorld. The NOx emission standards required by the construction permit is 11 ppm at 15% O₂. Blue Sky Environmental performed the source testing in October 2016. The average NOx emission from Engine SCR was 22.3 ppm which does not meet the emission standard of 11 ppm. The NOx emission from Engine SCR plus Carbon-Bed was 0.4 ppm which meets the emission standard of 11 ppm. The ammonia emission from Engine SCR was 11.9 ppm which exceeds the emission standard of 11 ppm. However, the ammonia emission of Engine SCR plus Carbon-Bed was 0.31 ppm which meets the emission standard. The source testing result clearly shows that two carbon beds should be used to meet NOx and ammonia emission standards.

CleanWorld turned over the operation of the SATS digester facility to Glenbrooks Investment Holding, the major owner of the facility. CHA met with Glenbrooks regarding the postcombustion NO_x control system. If Glenbrooks plans to operate the engine, it requires the CHA post-combustion NO_x control system. Moreover, CHA proposed Glenbrooks for the reactivation of saturated GAC generated from the carbon filter of Bio-CNG system and NO_x removal.

If Glenbrooks decides to operate the engine, CHA will help it to relocate the cooling tower installed at the top of equipment container. Also, temporary piping connecting exhaust gas to GAC adsorbers will be replaced by permanent piping. The entire postcombustion NO_x control system will be turned over to Glenbrooks or a new operator. The electricity distribution panel is located inside the container. After this equipment is removed, the equipment container will be transported back to CHA's lab.

If Glenbrooks decides not to operate the engine, CHA will remove piping connecting exhaust blower and heat exchanger to the first-stage adsorber. Piping will be removed from and to the stack inlet to the heat exchanger, blower and two GAC adsorbers. Piping will also be removed from the cooling tower to heat exchanger. The cooling tower installed at the top of the container will be removed. Then, CHA will transport all postcombustion NO_x control equipment and container to CHA's lab.

2.9 Technology/Knowledge Transfer Activities

The goal of this task was to develop a plan to make the knowledge gained, experimental results, and lessons learned available to the public and key decision makers. The overall goal is to commercialize the pre-and postcombustion NO_x control technology demonstrated under this California Energy Commission program. Thus, it is important to transfer the field test results to the targeted market sector and potential outreach to end users, utilities, and regulatory agencies.

The effective means of distributing results from this California Energy Commission funded program to the public is through presentations at topical and related technical conferences as well through publications. It is important for potential end users and regulatory agencies to be aware of pre-and postcombustion NO_x control microwave technology and field-testing results.

To pursue the commercialization of pre- and post-combustion NO_x control, CHA identified engine companies, biogas project developers, and regulatory agencies. CHA prepared the presentation of the field test results and advantages of microwave technology.

CHA prepared initial and final fact sheets and submitted these to the Commission agreement manager. The plan to present the field test results to the conference and regulatory agencies was also prepared. CHA will prepare the paper to publish lab and field test results and submit to an environmental journal such as the *Journal of Environmental Sciences and Chemical Engineering*.

2.10 Production Readiness Plan

This task determines the steps that will lead to the manufacturing of technologies developed in this project or to the commercialization of the results of the project. The overall goal is to commercialize the NOx control technology demonstrated under this California Energy Commission program. Thus, it is important to initiate the activities to scale-up the microwave reactor system and develop the market sector and business plan for commercialization.

The CleanWorld's SATS BioDigester site is a strategic location for continued testing and refinement of equipment, as well as development of the market service business revenue. It supplies a source of GAC that requires reactivation and minimizes the logistics of testing. CHA submitted the proposal to Glenbrooks to regenerate GAC used in the NOx adsorbers and Bio-CNG filter.

The CleanWorld's SATS digester site allows the CHA Corporation to do a proof of concept project on exhaust gas cleaning using GAC. CHA and Tecknikon (TEC) agreed to form a new company to commercialize CHA's technology for microwave regeneration of GAC. TEC will lead development and assessment of the business plan. CHA will support TEC as necessary.

SMUD has been supporting CHA's microwave technology development for more than 10 years. SMUD is evaluating the feasibility to commercialize the microwave technology in the biogas area. CHA will continue working with SMUD to commercialize the microwave technology related to upgrading of the biogas and removing of NOx, SO₂, and VOCs from engine exhaust.

CHAPTER 3:

PROJECT OUTCOMES

3.1 Field Testing Results

3.1.1 H₂S Removal Testing

The goal of the microwave H₂S removal testing was to demonstrate that the microwave-GAC reactor could completely remove and decompose H₂S and other sulfur impurities in biogas to prevent sulfur poisoning of the nickel catalyst. The biogas produced from CleanWorld digester contains about 40 ppm dimethyl sulfides and 36 ppm dimethyl disulfides. These sulfur impurities are also decomposed in the microwave-GAC reactor. The biogas is a promising candidate for producing H₂ for fuel cells. To evaluate the feasibility of the microwave-GAC reactor, the H₂S removal efficiency needs to be obtained as a function of biogas flow rate at 3 kW microwave power. The goal was also to find the maximum biogas flow rate that could destroy H₂S in a 3-inch quartz tube reactor with 3 kW microwave energy. The CHA Corporation would like to determine if this technology will be more economical than adsorbent-based biogas cleanup technologies.

The H₂S concentration of biogas before the final GAC filter was 20 ppm which was much lower than expected. The H₂S removal tests were conducted at 109 and 164 L/min (3.8-5.8 cfm) biogas. The H₂S was destroyed and could not be detected with Draeger tube. Due to the small pipe (1/4-inch diameter), the biogas flow rate could not be increased to greater than 164 L/min. In addition, the H₂S concentration of biogas after the primary H₂S scrubber was too low to determine the limit or the optimum process condition for the microwave destruction. It is necessary to install a larger diameter inlet pipe to the primary H₂S scrubber. It is also necessary to install piping and a water separator to test biogas that contains higher H₂S concentration. The biogas before the primary scrubber has H₂S in the range of 200-800 ppm.

The primary H₂S scrubber uses sulfur removal media followed by GAC filter. The sulfur removal media in the primary H₂S scrubber and GAC in the secondary H₂S removal filter must be replaced when saturated with H₂S. Also, biogas from landfill and wastewater treatment contains siloxanes. Siloxanes must be removed to protect the engine and postcombustion NO_x control catalyst. It is more difficult to remove siloxanes because sulfur removal media is not effective to remove siloxanes. The microwave-GAC reactor could destroy H₂S and siloxanes without using adsorption media. If the microwave-GAC reactor is scaled up to handle a higher biogas flow rate, it will be much cheaper than using conventional adsorbent technologies. The H₂S test result demonstrated the feasibility of handling larger biogas flow rates in the microwave reactor but the test must be conducted with biogas containing higher H₂S concentration.

3.1.2 Microwave Steam-Reforming Field Test

After problems with microwave generators were solved, CHA started microwave steam reforming tests with biogas withdrawn from the GAC filter inlet at the Bio-CNG facility. The

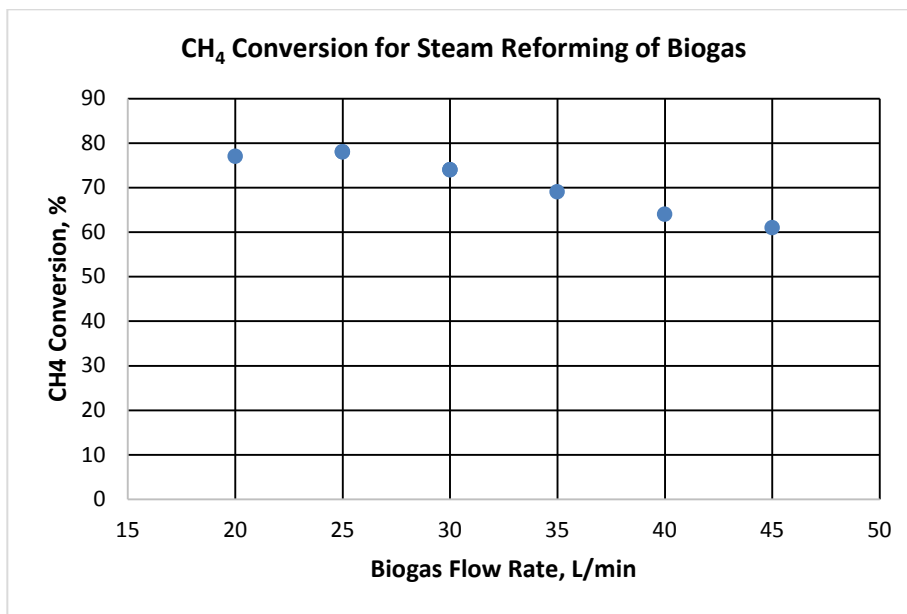
biogas had very low CH₄ concentrations ranging 41% to 60%. The research team conducted the steam reforming tests with various flow rates using biogas consisting of 47.2% CH₄ and 52.8% CO₂. Table 3 presents the CH₄ conversion and H₂ production using this biogas. Figures 23 and 24 present respectively CH₄ conversion and H₂ production at various biogas flow rates.

As shown in Table 3 and Figure 23, the CH₄ conversions were 78% and 74% for the biogas flow rate of 25- and 30 L/min, respectively. When biogas flow increased to 40 L/min, the CH₄ conversion decreased to 64%.

Table 3: Test Result From Microwave Steam Reforming of Biogas

Biogas Composition								
Methane, %	45.8	47.20	47.2	47.2	47.2	47.20	47.2	47.2
Carbon dioxide, %	49.7	52.80	52.8	52.8	52.8	52.80	52.8	52.8
Biogas flow rate, L/min	20	25	25	30.0	30	35	40	45
CH ₄ Conversion, %	77	78	78	74.0	74	69	64	61
H ₂ production, L/min	19.1	20.5	30.3	29.8	28.6	27.4	27.1	27.9
Product Gas Composition								
H ₂ , %	48.83	49.05	54.76	49.86	49.86	47.73	40.35	38.28
CH ₄ , %	5.38	5.71	4.76	6.08	6.08	6.5	10.02	11.45
CO, %	0.6	0.88	0.93	1.26	1.26	1.27	1.48	1.63
CO ₂ , %	45.19	44.36	39.55	42.80	42.8	44.5	48.15	48.64

Figure 23: Methane Conversion vs. Biogas Flow Rate

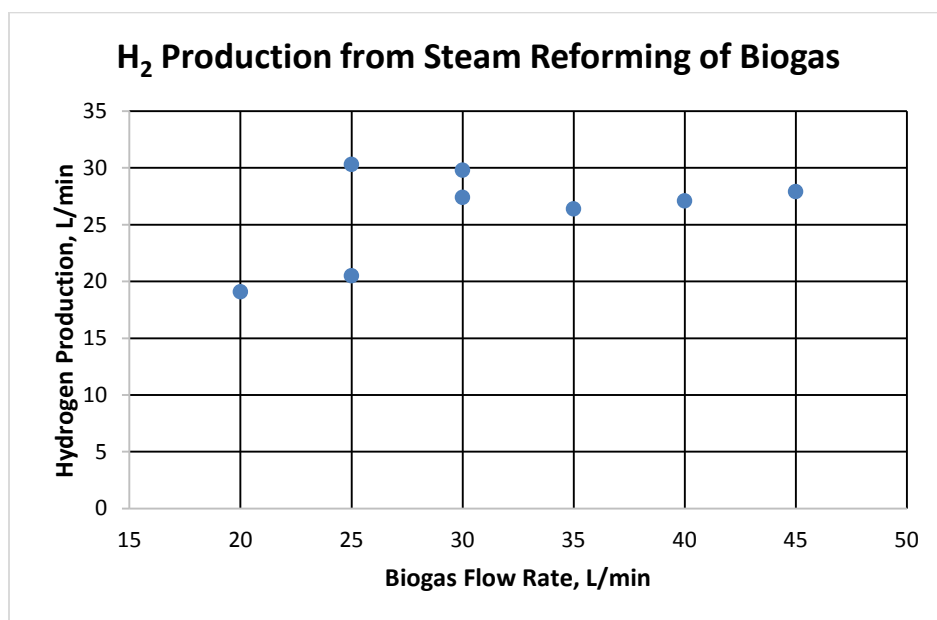


The H₂ production rate at 25 L/min of biogas was lower than expected. Thus, this test and the test with 30 L/min of biogas were repeated to check the H₂ production rate. The H₂ production at 25 L/min biogas was 20.5 L/min for the first run but increased to 30.3 L/min for the second run. The biogas temperature to the reformer at the first run was 955°F (512.8°C) but increased to 976°F (524.4°C). However, the CH₄ conversion to H₂ was the same, suggesting that the CH₄

concentration in the biogas for the first run was lower than the second run. CHA did not analyze the inlet biogas for every run. The H_2 production rates at 30 L/min of biogas were 29.8 and 28.6 L/min for the first and second run, respectively. The difference between these two runs is within experimental error.

The CH_4 conversions were comparable to the lab steam-reforming result described earlier. However, the H_2 production rates were much lower than lab result due to lower CH_4 concentration of biogas. At least 70 L/min H_2 production is needed for the precombustion NOx control test. The CH_4 concentration of biogas was 47.2% but the lab-simulated biogas had 66.6% CH_4 concentration. To increase the H_2 production rate, it was necessary to use Bio-CNG produced by CleanWorld.

Figure 24: Hydrogen Production vs. Biogas Flow Rate



The biogas and Bio-CNG were used to cool the reactors when the reforming test was completed. A part of biogas or Bio-CNG passing through high temperature catalyst bed without steam was decomposed and produced carbon black that reduced the methane conversion. The reforming catalyst in steam reformer R2 was replaced with a new catalyst. Also, the water-gas shift catalyst was added to make up any loss. After the water-gas shift catalyst was added to R3, the carbon monoxide concentration was reduced from 2-5% to 0.5-1.0%. The methane conversion did not increase.

After the container and electrical connections were installed, the mass flow controller malfunctioned. Because of limited budget and time required, repairing the mass flow meter was not practical. Thus, the rotameter that was calibrated with air was used. The Bio-CNG flow rate showing in the rotameter was lower than the actual volume flow rate because the CH_4 density is much lower than air. It was found that the correction factor is 1.35 for converting the

rotameter reading to correct volume flow rate of Bio-CNG. Because the carbon balance was used to calculate the reformer product gas flow rate, the inlet Bio-CNG flow rate affected the calculation of the H_2 production rate.

The volume ratio of nickel catalyst to SiC was decreased from 2.0 to 1.0 to increase microwave adsorption that provides more energy to the steam-reforming reaction and insulated the R2 mail box microwave applicator. However, the insulation of R2 mail box induced its thermal expansion that caused failure of the reactor seal. Consequently, the insulation was removed from the mail box applicator.

A new nickel catalyst was prepared since the catalyst previously used was prepared one year before. The steam reforming R2 reactor was charged with the same volume of SiC and new nickel catalyst. A series of microwave steam reforming tests were run. The CH_4 conversion decreased more than 10% and H_2 generation decreased by 10 L/min. The Bio-CNG flow of 40 L/min did not provide higher H_2 generation. Three batches of nickel catalyst and two different ratios of nickel catalyst to SiC were tested. None of these changes increased CH_4 conversion and H_2 generation rates.

The R2 inlet temperature of steam and Bio-CNG was maintained at 900-1,000-degree F, the same temperature range as the lab-tests. However, the microwave steam reforming at the field tests yielded lower CH_4 conversion. To increase CH_4 conversion, air was introduced into R1 reactor. Adding air to R1 increased the CH_4 conversion however, did not increase the H_2 production. GAC in R1 was replaced with SiC to initiate a partial oxidation of CH_4 to produce CO. The CH_4 was completely oxidized with air in the SiC bed and did not produce CO. Thus, the SiC in R1 reactor was replaced with GAC. It is not clear why the field tests yielded lower CH_4 conversion than lab-tests for the same CH_4 flow rate.

None of options tested increased the CH_4 conversion and H_2 production. The R2 reforming reactor was charged with the mixture of nickel catalyst and SiC with volume ratio of 2:1. Then, a series of microwave steam reforming tests were carried out with Bio-CNG flow rate of 27-34 L/min for numerous days in October and November to produce the H_2 at a steady state. CleanWorld had problems with the Bio-CNG system in October, and it was necessary to fill the tank with CNG in the filling station next to the Bio-CNG system. The CNG tank for microwave reforming tests was used until field testing was completed.

The CH_4 conversion and H_2 production were measured at five CNG flow rates. Table 4 presents the result from this series of tests. Figure 25 and 26 present CH_4 conversion and H_2 production rate as a function of CNG flow rate, respectively.

Table 4: Result of Steam Reforming With Various CNG Flow Rates

R2 Inlet Gas Temp, 0F	1,010	1023.00	1,028	1024.00	
CNG, L/min	13.5	20.3	27	33.8	40.5
Steam, kg/h	3	3.3	3.5	4.0	4.3
CH4 Conversion, %	75.3	70.0	65.8	56.3	44.2
H2 Production, L/min	36.6	48.1	66.7	67.3	80.0
H2 Production, cfm	1.3	1.7	2.4	2.4	2.8
Product Gas Composition					
H2, %	73.1	70.4	71.2	68.0	66.5
CH4, %	6.6	9.0	9.9	14.0	18.7
CO, %	1.7	1.8	1.5	1.5	1.1
CO2, %	18.6	18.9	17.4	16.6	13.8

Figure 25: Methane Conversion as a Function of CNG Flow Rate

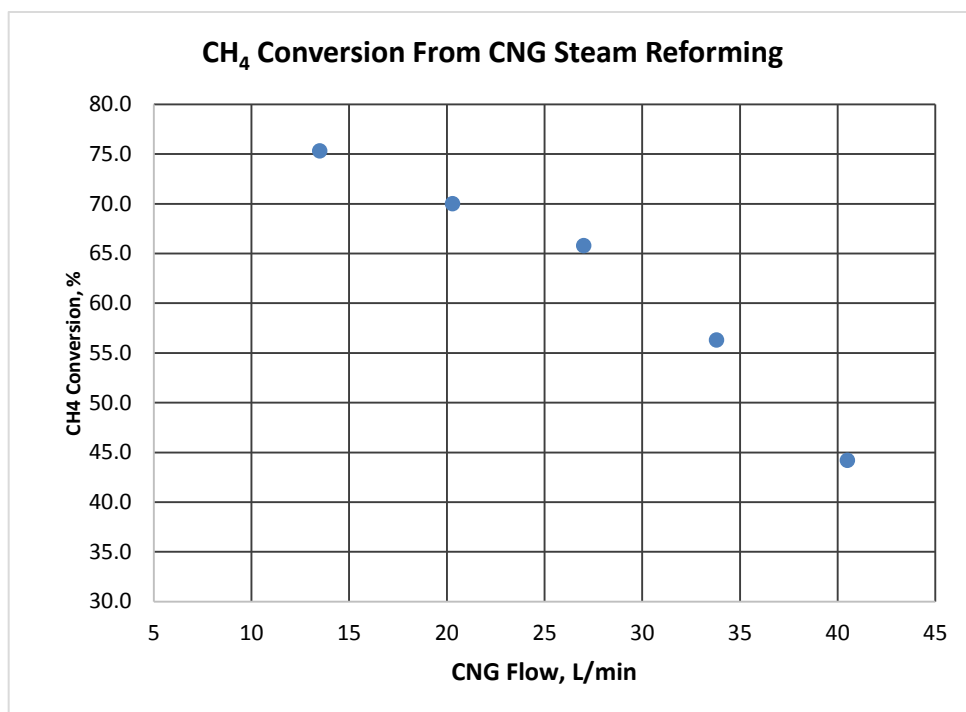
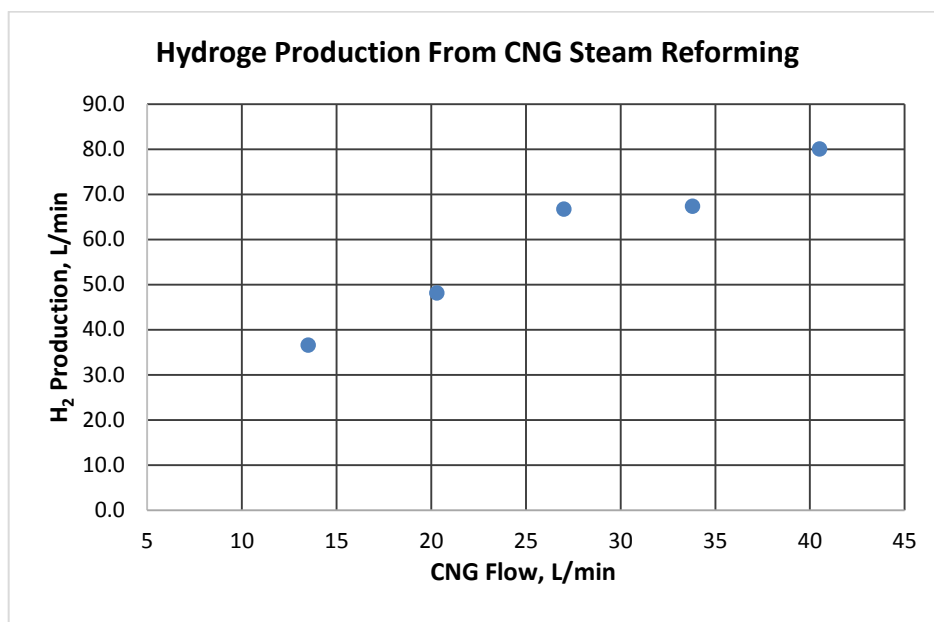


Figure 26: Hydrogen Production as a Function of CNG Flow Rate



As shown in Table 4 and Figures 25 and 26, the CH₄ conversion decreased from 75% to 44% but the H₂ production increased from 37 L/min to 80 L/min as CNG flow rate increased from 14 L/min to 41 L/min. The CH₄ conversions and H₂ productions were lower than lab tests at given CH₄ flow rates. The heat loss could be higher at the field test site than at the lab and would reduce the conversions. The CH₄ concentrations of reformer gas shown in Table 4 are higher than those of the lab tests, probably due to lower conversion. Also, CO₂ concentrations were lower than those of the lab tests also due to lower CH₄ conversion. The mass flow controller was used for the labtest but malfunctioned after the container was installed at the CleanWorld site. Rotameter readings were adjusted to obtain correct CNG flow rate.

Steady-state reforming tests were run with 27 L/min and 34 L/min CNG flow rates for 10 days and introduced produced H₂ into biogas engine inlet to be ready for precombustion test. Every day the reforming test were started with 14 L/min and increased to 27 or 34 L/min when R2 inlet gas temperature increased to 950°F (510°C). The average CH₄ conversions were 63% and 53% for 27 L/min and 34 L/min, respectively. The H₂ production rates were 59 L/min and 66 L/min for CNG flow rates of 27 L/min and 34 L/min, respectively. These conversions were lower than conversions obtained earlier. It was not clear why the long term test conversions were lower.

3.1.3 Precombustion NOx Control

The pre-combustion NOx control test sought to demonstrate that the application of HALO to biogas engine could reduce the NOx emission greater than 70%. After completing tests for the steady production of H₂, CHA conducted the precombustion NOx control tests.

CleanWorld operates a 190 kW biogas engine but was not allowed to change the air/fuel ratio. The 2G engine company has direct control over the air/fuel ratio. This was the main difficulty for conducting the pre-combustion NOx control test. Western Energy represents 2G in California. On December 7, 2016 Jeremy Webb of Western Energy came to the CleanWorld site to change the air/fuel ratio to run the engine with H₂ injection. He ran the engine for about two hours however, could not get a hold of 2G personnel to increase the air/fuel ratio greater than 1.44. He came back to the CleanWorld site on December 15 and ran the engine for five hours and changed the air/fuel ratio. He ran the engine again on December 16 for five hours. Both days the engine stopped because CH₄ concentration of biogas decreased to 40%. Webb returned to the CleanWorld site on December 22 to continue the precombustion NOx control test but could not start the engine because the engine breaker failed. Therefore, it was necessary to conclude pr-combustion NOx control testing.

Table 5 presents the results from the three-day precombustion NOx control tests. The hydrogen was injected at 2.4-cfm for the December 7 test. Because of trouble with the heat tape, the H₂ injection for December 15 test was reduced to 2.1 cfm. The H₂ injection was increased to 2.6 cfm for the December 16 test. The engine started at 15 cfm CH₄ flow rate but the rate increased to 17 cfm when engine stopped. The CH₄ concentration of biogas started at 58-60% and decreased to 40-42%. Thus, the average biogas flow rate to engine was 32 cfm. The engine shut down when CH₄ content of biogas decreased to below 42%. The lower CH₄ content of the biogas reduced the test time to five hours.

Table 5: Result From Pre-Combustion NOx Control Tests at 100-kW

Date	Time	Exhaust O ₂ , %	Air/Fuel Ratio	NOx at 15% O ₂	Note
7-Dec-16	11:20	6.10	1.40	130	H2 in CH4 was 16%
	11:27	6.30	1.42	119	
	11:30	6.10	1.40	146	
	11:43	7.10	1.42	104	
	11:45	7.20	1.44	92	
15-Dec-16	7:20	6.30	1.43	115	H2 in CH4 was 14%
	7:24	6.10	1.41	127	
	8:00	6.90	1.49	146	
	8:05	7.30	1.53	84	
	8:41	7.60	1.57	47	
	8:53	8.20	1.64	35	
	9:36	7.50	1.56	40	Engine ran for 3 hrs
16-Dec-16	8:26	6.30	1.43	239	H2 in CH4 was 16%
	8:34	7.00	1.50	99	
	9:00	7.00	1.50	61	
	9:07	7.20	1.52	45	
	9:10	7.30	1.53	38	
	9:15	7.60	1.57	28	
	9:30	6.70	1.47	67	Ran 3 hrs, very stable
	12:37	6.80	1.48	51	

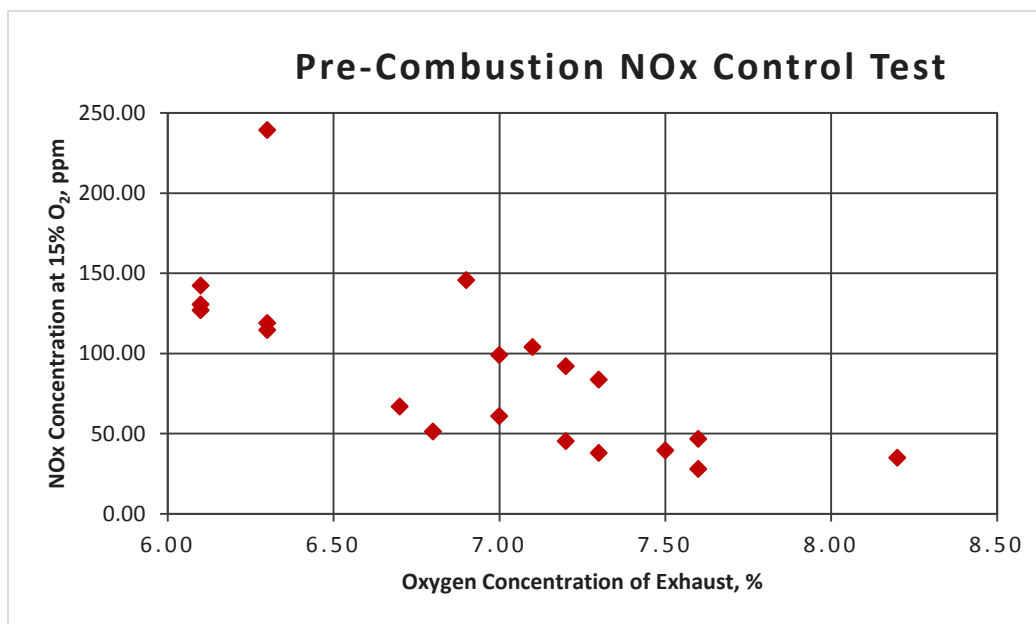
Figure 27 shows NOx emission as a function of O₂ concentration of engine exhaust. As shown in this figure and Table 5, the NOx emission decreased as the O₂ concentration of the exhaust

increased. The lowest NOx emission of 28-35 ppm was obtained when the exhaust O₂ concentration was 7.6-8.2% (air/fuel ratio =1.57-1.64). However, the engine operation was not stable with this air/fuel ratio. The engine ran very stable with the air/fuel ratio of 1.47 with 2.6 cfm H₂ injection. The NOx emission with stable engine operation was 67 ppm at 15% O₂, which represents a 72% reduction from 239 ppm before the air/fuel ratio increased. The specific goal of pre-combustion NOx test was to achieve the NOx reduction of greater than 70%.

TIAX tested the BIOHALO system with a 75 kW engine with synthetic landfill biogas and synthetic reformat prepared using bottled gas. With 6% LHVH₂/CH₄ supplement, 20-30 ppm NOx emission was obtained at 7.5-8% O₂ in the engine exhaust. When the LHVH₂/CH₄ increased to 7.5-15%, the NOx emission was reduced to 5-10 ppm at 8-10% O₂ concentration. The H₂ volume concentration in CH₄ equivalent to 6% LHVH₂/CH₄ is 18%.

Table 5 shows that the lowest NOx emission with 16% H₂ supplement was 28 ppm when the air/fuel ratio was 1.57 with 7.6% exhaust O₂. This NOx emission was very close to TIAX's result with synthetic landfill biogas and synthetic reformat. If the H₂ injection rate increases to 4.5 cfm, it is possible to reduce the NOx emission to 10 ppm.

Figure 27: NOx Emission as a Function of Exhaust O₂ Concentration



It was understood that TIAX ran engine with 8-10% H₂ supplement in natural gas that meant to be the volume concentration. However, it was discovered from the final report of the California Energy Commission project that TIAX ran the engine 10% LHVH₂/CH₄ that is equivalent to 30% H₂ concentration in CH₄ in simulated landfill biogas. Because of this misunderstanding CHA prepared to inject H₂ into biogas at 10% by volume. Thus, the CHA reforming system was not able to meet H₂ production of 4.5-cfm to provide 10% LHVH₂/CH₄.

3.1.4 Post-Combustion NOx Control

The goal of the integrated system of pre- and postcombustion NOx control is to meet the SCAQMDs Rule 1110.2 (average NOx emission of 11 ppm) soon and ultimately meet CARB 2007 standards (average 5 ppm NOx emission). The second goal of the post-combustion NOx control is to recover heat from the exhaust for beneficial use to increase the combined efficiency of the engine. The 2G Cenergy engine package is equipped with a very flexible heat recovery package, including a heat exchanger installed after the SCR. But this heat exchanger is not connected to the digester heating system.

3.1.4.1 NOx Removal by SCR and One GAC Adsorber

CleanWorld operates a 190 kW biogas engine but had many operational and maintenance problems including urea injection that triggered the automatic shutdown. An engine specialist from Western Energy visited CleanWorld in September and replaced the expansion tank to solve problems with cooling water pressure. But the cooling water pressure caused problems continuously for starting the engine. CleanWorld checked expansion tank again and filled it to 11.5 psig while isolated from the cooling water. The biogas flow to engine was restricted by condensate in the inlet biogas line and biogas pressure regulator. The biogas pressure regulator was removed to increase biogas flow rate. Because of unstable engine operation, the post-combustion NOx control test to measure NOx adsorption capacity of GAC bed did not begin until August.

The heat exchanger and condensate water separator was operated whenever engine was running. The exhaust gas temperature prior to the adsorber was in the range of 1050 to 1090 F. Most of the exhaust condensate was collected in the heat exchanger condensate separator but a small portion of condensate was collected in the pipe to the adsorber. To collect this condensate, an additional condensate separator was built using a 55-gallon drum and was installed after the main heat exchanger condensate separator.

The O₂ concentration of exhaust was measured at three blower speeds to determine the exhaust flow rate. When the blower speed increased above 42%, the O₂ concentration increased. The exhaust flow rate at 140 kW engine power with 42 cfm biogas or 23 cfm CH₄ was calculated at 300 cfm.

Two GAC beds were installed for the postcombustion NOx control but only one adsorber was used to capture NOx after SCR. The post-combustion NOx control test with one GAC bed began on August 3. The adsorption test was run almost every day if the engine did not have operational problems. The total NOx adsorption time for one GAC adsorber in August was 61 hours. Figure 28 presents the NOx concentrations of inlet and outlet gas of the GAC bed corrected to 15% O₂. The NOx concentration of the gas from SCR (inlet to GAC bed) varied between 5 to 32 ppm. Figure 28 shows that SCR alone will not meet the emission standards of 11 ppm for 50% of the time of engine operation. The performance of SCR was very sensitive to engine power and the CH₄ content of biogas. Adding GAC beds will ensure that the NOx emission will meet the 11 ppm emission standards.

Figure 28: NOx Content of Inlet and Outlet of a Single GAC Bed

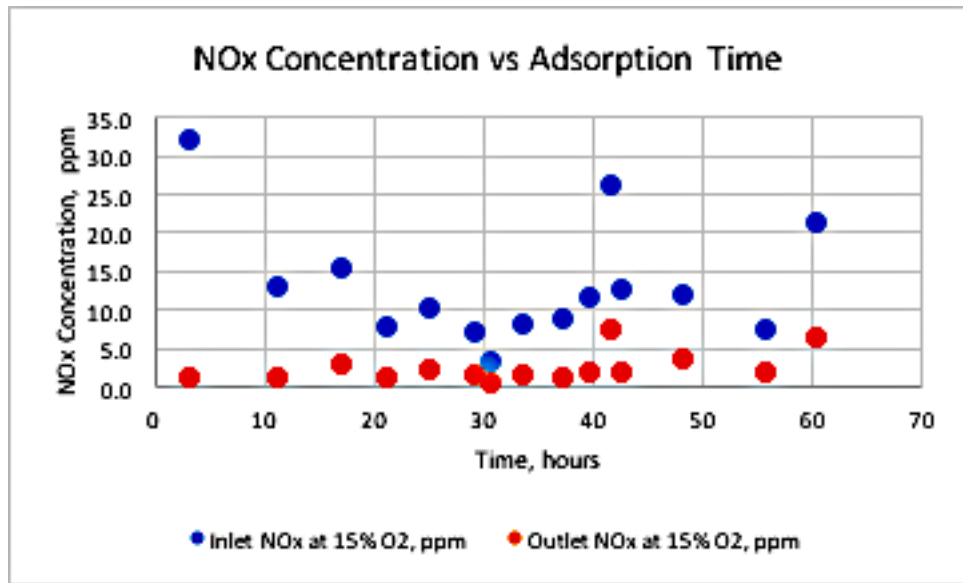
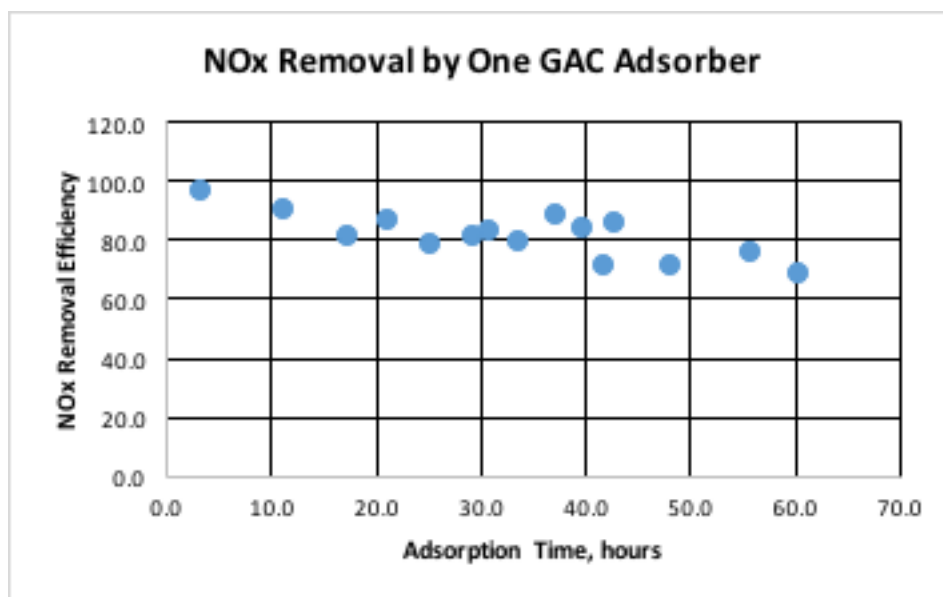


Figure 29 presents the NOx removal efficiency for a single GAC bed that was used with the SCR. This figure shows that the NOx removal efficiency by one GAC bed was greater than 80% for 40 hours but started to decrease to 70% as the adsorption time increased greater than 42 hours. The average NOx removal efficiency for 61 hours was 80%. The amount of NOx adsorbed by the GAC bed was calculated at 45 standard cubic feet (scf) or 5.7 pounds for 61 hours.

The result from adsorption test using one GAC bed combined with SCR indicates that the GAC bed could be used with the SCR to meet the Rule 1110.2 NOx emission standards. Since the SCR does not have an oxidation catalyst, VOCs in exhaust will not be removed. The GAC bed will remove the VOCs and adsorb the ammonia generated from SCR. The GAC will also remove SO₂ from exhaust.

Figure 29: NO_x Removal Efficiency vs. Adsorption Time for a Single GAC Bed



3.1.4.2 Source Testing

Two GAC beds were installed and operated for the post-combustion NO_x control to be ready for the source testing. Blue Sky Environmental, Inc. performed the source test on October 10 to determine compliance of the 190-kW biogas engine in respect to SMAQMD request. The emission standards are presented in Table 1. Source testing was performed for Engine SCR emissions and Engine SCR plus carbon bed emissions. Table 6 presents average emission data from three 60-minute source tests.

Table 6: Source Test Result

Pollutant	Engine SCR Average Emissions	Engine SCR plus Carbon Bed Average Emissions
NO _x	22.3 ppm corrected to 15% oxygen (0.22 g/BHp-hr)	0.4 ppm corrected to 15% oxygen (0.003 g/BHp-hr)
CO	62 ppm corrected to 15% oxygen	65 ppm corrected to 15% oxygen
VOC	No hydrocarbons greater than C2 were found	No hydrocarbons greater than C2 were found
Ammonia	11.9 ppm corrected to 15% oxygen	0.31 ppm corrected to 15% oxygen

As shown in Table 6, average NO_x emission from Engine SCR was 22.3 ppm corrected to 15% oxygen which does not meet the emission standard of 11 ppm corrected to 15% oxygen. All concentration data given are values corrected to 15% oxygen. NO_x emission from Engine SCR

plus Carbon Bed was 0.4 ppm which meets the emission standard of 11 ppm. Both engine SCR and engine SCR plus Carbon Bed meet CO emission standard of 250 ppm. Hydrocarbons greater than C_2 were not found in the sample taken from both outlets. Thus, VOC was not found in both emissions. Ammonia emission from Engine SCR was 11.9 ppm that exceeds the emission standard of 11 ppm. However, ammonia emission of Engine SCR plus Carbon Bed was 0.31 ppm which meets the emission standard. The source testing results clearly show that Engine SCR plus Carbon Bed should be used to meet NOx and ammonia emission standards. The GAC bed adsorbed ammonia very well and could be used to remove ammonia from exhaust from SCR. Also, the source testing result confirms that two GAC beds in series could be used to meet the SCAQMD's Rule 1110.2 NOx emission standards if the NOx emission from SCR exceeds 11 ppm.

Blue Sky Environmental measured concentrations of sulfur components in the engine inlet biogas. The H_2S concentration was negligible but the concentration of other sulfur impurities including dimethyl sulfide and dimethyl disulfide was 78 ppm.

3.1.4.3 NOx Removal by GAC Beds Without SCR

The main objective for the post-combustion NOx control test was to find the adsorption capacity of GAC bed when the time averaged NOx emission reaches 5 ppm at 15% O_2 . After the source testing, the post-combustion NOx control test continued using a two GAC beds in series. The maximum capacity of biogas engine at the CleanWorld site is 190 kW. However, the NOx concentration of exhaust before SCR was greater than 300 ppm that exceeded the limit of the CHA NOx meter. Thus, researchers have conducted NOx adsorption test with SCR when engine ran at 190 kW. When the engine was run at 100 kW, the NOx concentration of exhaust before SCR was below 300 ppm. Thus, adsorption tests were run for many days with engine running 100 kW to determine the GAC adsorption capacity with and without with hydrogen injection. Table 7 present an example of daily test data recorded. Daily average test data were used to calculate time-averaged NOx emission.

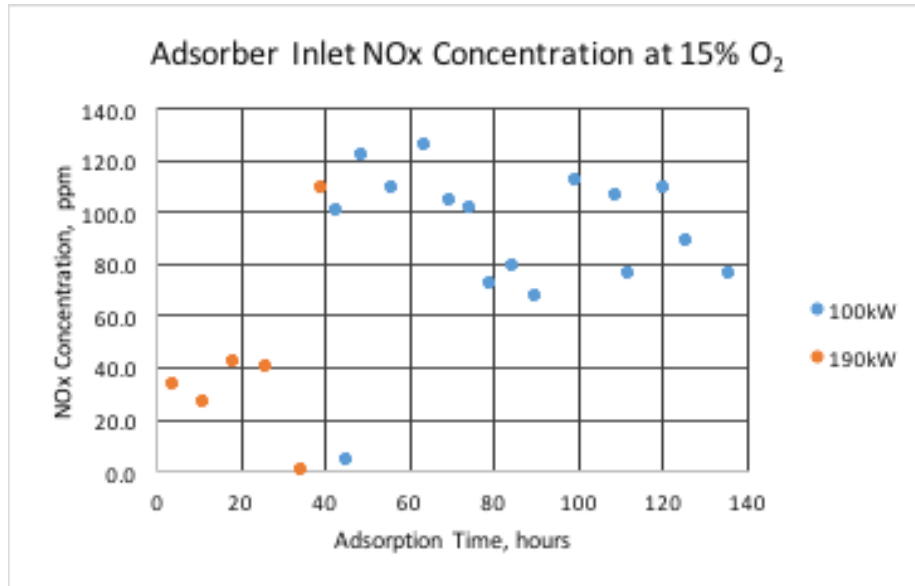
Figure 30 present daily average NOx concentration of engine exhaust entering the first stage GAC adsorber as a function of adsorption time for the post-combustion NOx tests using two GAC beds in series. To see the effect of H_2 injection, the last six tests were conducted with H_2 injection. As shown in Figure 30, H_2 injection without adjusting air/fuel ratio increased the engine exhaust NOx concentration, probably due to the decrease in the actual air/fuel ratio caused by H_2 injection. The SCR was operated when the engine ran at 190 kW but bypassed at 100-kW.

Table 7: Example of Daily Data Recorded for Postcombustion NOx Control Test

Date	11/15/16	started engine and ads. at 7:30					Stop 15:00
Time	8:00	9:00	10:00	11:00	12:00	13:00	Daily Average
CH ₄ flow shown at engine, m ³ /h	27	28.8	32.2	33.7	33	34.7	31.57
CH ₄ flow, cfm	15.89	16.95	18.95	19.83	19.42	20.42	18.58
Biogas CH ₄ conc. %	62.9	61.4	59.8	58.9	58.6	58.1	59.95
Digester header biogas, cfm	210	215	203	175	260	249	218.67
Flare biogas, cfm	185	192	180	148	194	173	178.67
CH ₄ conc. of flare biogas,	62.6	61.2	59.6	58.7	49.1	50.1	56.88
Biogas to 200 CNG Header, cfm	0	0	0	0	39	29	
CH ₄ to flare	115.81	117.50	107.28	86.88	95.25	86.67	
CH ₄ flow to engine	16.28	14.51	14.11	16.20	34.25	41.15	22.75
1st GAC Bed inlet							
O ₂ concentration, %	6.75	6.53	6.4	6.31	6.26	6.37	6.44
Stoichiometric air, cfm	151.33	161.42	180.47	188.88	184.96	194.49	176.92
Excess air, cfm	68.60	70.01	76.39	78.56	76.13	82.20	75.31
Total air, cfm	219.92	231.42	256.86	267.44	261.09	276.69	252.24
Dry exhaust, cfm	213.41	225.13	250.66	261.45	255.39	271.00	246.17
Air/fuel ratio	1.45	1.43	1.42	1.42	1.41	1.42	
Power, kW	100	100	100	100	100	100	
NO, ppm	225.8	242.1	268.5	254.6	251.3	249.4	248.62
NO ₂ conc., ppm	5.2	5.2	6.5	5.1	5.6	8.9	6.08
NOx, ppm	235.2	244.6	270.6	259.7	257.7	257.4	254.20
NOx at 15% O ₂							109.08
1st bed outlet or 2nd bed inlet							
NO, ppm	61.3	75.4	102.5	103.6	107.8	75.5	87.68
NO ₂ , ppm	0	0.3	1.1	0.5	0.8	0.8	0.58
NOx, ppm	62.1	76.1	103.8	104.1	109.2	76	88.55
NOx removal, %	73.60	68.89	61.64	59.92	57.63	70.47	65.36
NOx at 15% O ₂ , ppm							38.00
NOx adsorption rate, cfm	0.036941	0.037935	0.041810	0.040682	0.037926	0.049159	
NOx adsorbed, cubic feet (cf)							18.72
2nd bed outlet							
NO, ppm	2.7	3.9	7.8	10	11.2	7.5	7.18
NO ₂ , ppm	0	0	0	0	0	0	0.00
NOx, ppm	2.4	3.9	8.1	9.7	10.9	7.4	7.07
NOx removal, %	96.14	94.88	92.20	90.68	90.02	90.26	92.36
O ₂ , %	6.77	6.63	6.38	6.3	6.22	6.21	6.42

NOx at 15%O ₂ , ppm							3.03
CO, ppm	275	320	364	369	371	373	345.33
NOx Adsorption rate, cfm	0.01274 1	0.01625 5	0.023 988	0.024 681	0.025 105	0.0185 90	
NOx adsorbed, cf							1.62

Figure 30: Exhaust NOx Concentration for Post-Combustion NOx Control



NOx concentrations of inlet and outlet of two GAC beds were measured every hour as shown in Table 7. From hourly concentrations and flow rates, the amount of NOx adsorbed by each of two GAC beds was calculated. Then, the cumulative amount of NOx adsorbed by GAC bed was calculated for each test day.

Using daily average NOx emission and exhaust gas flow rate, the amount of NOx emitted during testing was calculated for each testing day. Then, the cumulative NOx emitted to the given testing date was calculated. The time-averaged NOx emission was calculated for each test day by dividing total amount of NOx emitted to date by total adsorption time. Figure 31 presents the daily time-averaged NOx emission from the second stage GAC adsorber after two-stage GAC beds were used for post-combustion NOx control.

Figure 31 shows that time averaged NOx emissions reached 5 ppm at 15% O₂ 136 hours after the postcombustion NOx control test started with two GAC beds in series. However, the first adsorber ran for 61 hours before the second stage adsorber was connected to the post-combustion NOx control system. The first stage GAC bed adsorbed 35.8 pounds of NOx and the second stage bed adsorbed 16.2 pounds of NOx. Each bed was loaded with 1,675 pounds of GAC. The NOx adsorption capacity of the first GAC bed is 2.14%. The first GAC bed was removed from the postcombustion NOx control system and saturated GAC was reactivated.

When the engine ran at 100 kW, the NOx emission was lower even if the inlet NOx concentration was higher. Also, the NOx removal by GAC beds increased from 1.12 cubic feet per hour (cfh) to 3.37 cfh when the engine power decreased from 190 kW to 100 kW. The exhaust gas flow rates were 382 and 232-cfm for 190 kW and 100 kW, respectively. The GAC adsorber should be designed with the superficial gas velocity corresponding to 232 cfm (15 ft/min). This higher NOx adsorption rate was due to higher inlet concentration to GAC beds and longer contact time.

Figure 31: Time-Averaged NOx Emission vs. Adsorption Time

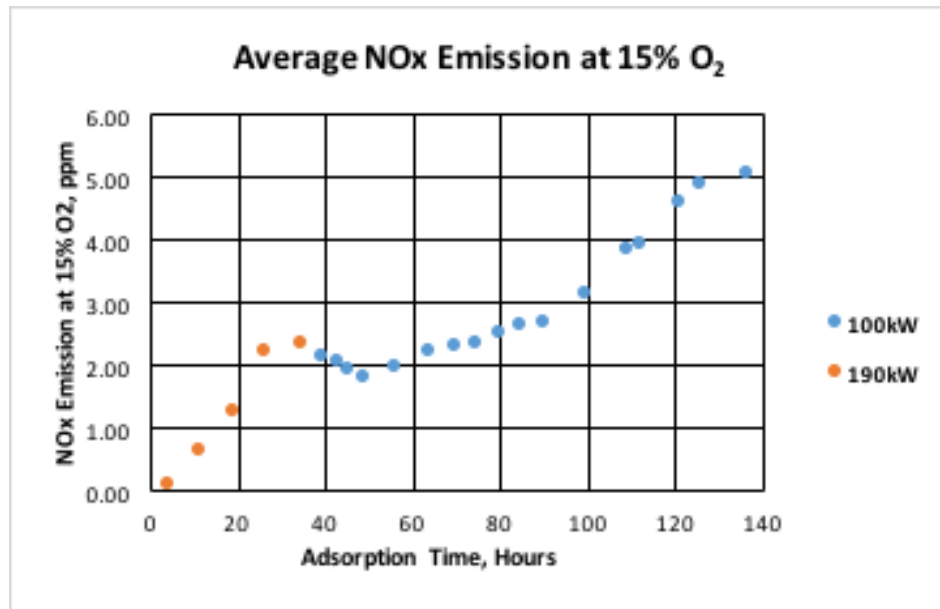


Figure 32 presents the average NOx removal efficiency by two beds as a function of adsorption time. The NOx removal efficiency for lower gas superficial velocity (15 ft/min) is greater than higher superficial gas velocity (25 ft/min), due to longer contact time of NOx with GAC. The first- stage GAC bed had higher concentration of NOx inlet than the second stage GAC bed.

Figure 32: Overall NOx Removal Efficiency vs. Adsorption Time

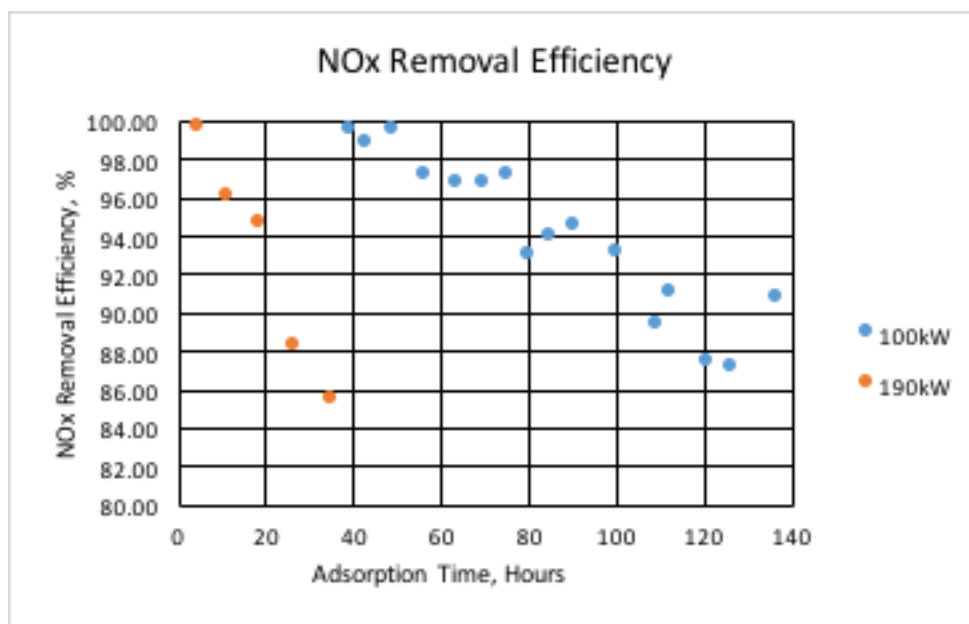
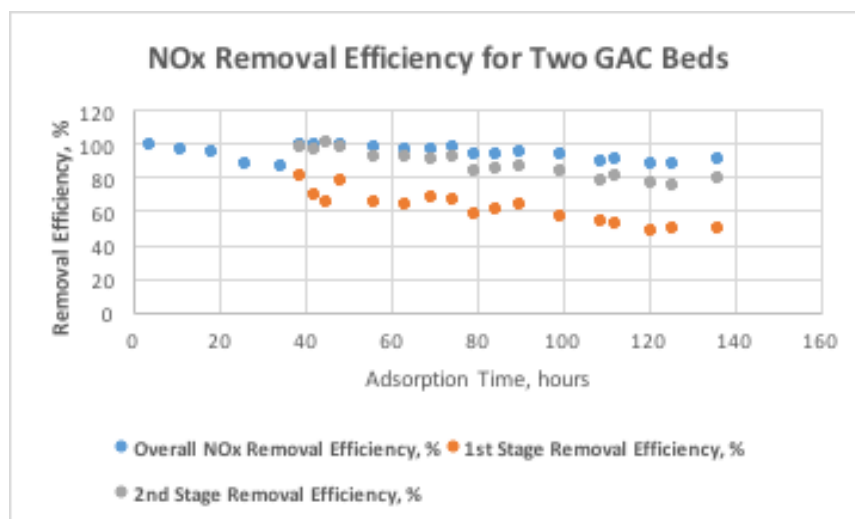


Figure 33 presents the NOx removal efficiency for each of the two beds as a function of adsorption time when the engine ran at 100 kW. The NOx removal efficiency of the first bed decreased from about 80% to 50% as the adsorption time increased from 40 to 136 hours. But the NOx removal efficiency of second-stage bed decreased from 100% to 80%. This result indicates that NOx removal efficiency is higher for lower inlet NOx concentration. Moreover, it suggests that NOx removal efficiency will be higher when GAC beds are used to remove NOx from exhaust passing through SCR to meet the 11-ppm current NOx emission standards or the 5 ppm future NOx emission standards. The NOx removal efficiency of the first bed is greater than 50% when the NOx emission from the second stage bed reaches 5 ppm. This observation suggests that the NOx adsorption capacity of the first bed will be greater if more GAC or larger numbers of adsorbers are used.

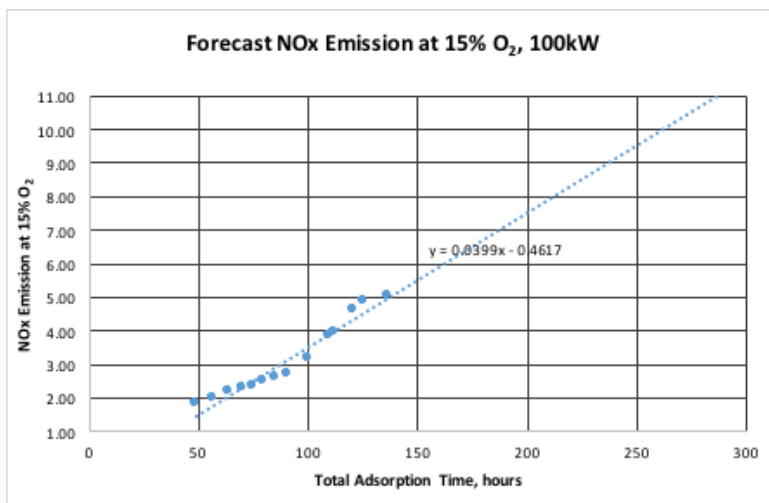
Figure 33: NOx Removal Efficiency for the First and Second Adsorbers



To find the adsorption time when the NOx emission reaches current emission standards of 11 ppm at 15% O₂, the NOx emission data in Figure 31 were extrapolated and shown in Figure 34. The equation shown in Figure 34 predicts that the average NOx emission will reach 11 ppm after 287 hours of adsorption time. Based on these test data, the amounts of NOx adsorbed were estimated at 75.6 and 45.9 pounds for the first and second-stage GAC beds, respectively. The NOx adsorption capacity of the first bed would be 4.5% when the NOx emission from the second bed reaches 11 ppm. This result suggests that GAC in the first-stage adsorber may be replaced every two months to meet the NOx emission standards.

Because of the engine breaker failure, it was necessary to conclude the field-testing of pre- and post-combustion NOx control. Even if the second stage adsorber was not saturated with NOx, GAC was reactivated in the second stage bed. Two GAC beds are filled with reactivated GAC and ready for Glenbrooks or ES Engineering to use to meet the NOx emission standards.

Figure 34: Extrapolated NOx Emission for Postcombustion NOx Control



3.1.5 Microwave Regeneration of NOx-Saturated GAC

When time-average NOx emission reached 5 ppm, the first GAC bed was removed from the postcombustion NOx control system and the NOx-saturated GAC was reactivated. The NOx-saturated GAC was transported into the top hopper and fed into the microwave reactivation reactor. About 1 cfm N₂ was introduced into the bottom hopper to remove NOx and VOC vapors released from GAC.

The NOx adsorbed in the GAC was desorbed by microwave energy in the reactivation reactor. A part of desorbed NOx in the sweep gas reacted with carbon by microwaves in the reactivation reactor. The remaining NOx in the sweep gas flowed into the De-NOx reactor charged with GAC and reacted with carbon by microwave energy. The NOx contained in the sweep gas reacts with carbon in both reactivation and De-NOx reactors to produce N₂ and CO₂ ($2\text{NOx} + \text{xC} \rightarrow \text{N}_2 + \text{xCO}_2$). The NOx concentration of the sweep gas from De-NOx reactor was lower than 5 ppm, confirming the complete destruction of NOx desorbed from GAC.

The concentration of total hydrocarbons (THC) in the sweep gas entering the De-NO_x reactor was 1,900-2,000 ppm. The THC concentration in the De-NO_x reactor outlet was not measured. The sweep gas passing through the De-NO_x reactor was combined with 1 cfm air and then flowed into the oxidizer. The oxidizer outlet gas had THC concentration lower than 50 ppm, indicating that 98% of VOCs released from saturated GAC was oxidized.

The second-stage GAC bed was also reactivated even though it was not saturated with NO_x. The average concentration of THC concentration of reactivation gas entering De-NO_x reactor was 432 ppm. The THC concentration of gas leaving De-NO_x reactor was 235 ppm, indicating that 46% of hydrocarbons was decomposed by microwaves in the De-NO_x reactor. This indicates that microwave energy combined with GAC decomposes not only NO_x but also higher hydrocarbons. Thus, the microwave-GAC reactor may be used to destroy non-methane hydrocarbons such as alcohols and ketones in biogas for Bio-CNG separation. Higher hydrocarbons must be removed from biogas to avoid contaminants in CNG. The oxidizer destroyed hydrocarbons and no hydrocarbons were detected in the gas leaving the oxidizer.

After completing reactivation, two GAC adsorbers were installed at the post-combustion NO_x control system. Two beds were filled with reactivated GAC and ready for ES Engineering to use to meet the NO_x emission standards.

3.1.6 Potential Improvements on Pre- and Post-Combustion NO_x Control System

This section describes items that caused operational problems during the pre- and post-combustion NO_x control tests. These problems must be corrected for the successful commercialization of the pre- and post-combustion NO_x control for biogas engines with microwave energy.

3.1.6.1 Microwave Steam Reformer

Steam reforming is a highly endothermic reaction and requires significant energy. The heat of reaction was supplied by microwaves. A double quartz tube reactor is used to reduce heat loss but heat loss from the double tubes is still too great to use microwave energy efficiently. It was not possible to insulate the mail box applicator to reduce heat loss because of thermal expansion compromising reactor seal. A 6 kW microwave generator can supply heat of reaction required to produce 120 L/min hydrogen. Because of high heat loss, only 80 L/min was produced. Also, it was difficult to increase CH₄ conversion greater than 65%. A new microwave reactor must be developed to reduce heat loss and increase the reactor throughput for successful commercialization of microwave steam reforming.

Biogas must be used to produce H₂ required for stable engine operation at higher air/fuel ratio. Because of low CH₄ concentration, the biogas flow rate is almost two times greater than CNG to produce H₂ required for pre-combustion NO_x control. The microwave reformer must be redesigned to handle higher throughput.

During the previous Energy Innovations Small Grant project, O₂ was added to increase CH₄ conversion. The conversion was increased but more CO was produced. Since NO_x formation

depends mainly on the combustion temperature, adding air to reformer inlet would act as diluent and would reduce excess air required to reduce NOx formation. During the steam-reforming test, a small amount of air was added to the inlet biogas to increase CH₄ conversion. The conversion increased but H₂ production did not increase. CHA did not pursue this test because of the low CH₄ concentration of biogas. It is necessary to investigate if adding air into inlet biogas increases H₂ production for pre-combustion NOx control. The microwave reactor must be able to process higher biogas flow to produce required H₂ from biogas.

3.1.6.2 Gas Heater

Because of the highly endothermic steam reforming reaction, it is necessary to heat the mixture of steam and biogas to about 1,000°F (537.8°C). With the current gas heater, the gas could be heated to about 700 °F. Thus, researchers had to install pre-and post-heaters using heat tapes; however, it took too long to increase the inlet gas-steam mixture to 1,000°F (537.8°C). The heat tapes were not reliable and should be used only temporarily. A more efficient heater must be found to increase the inlet gas temperature. For commercial operation, biogas or tail gas must be used rather than electricity to heat the inlet gas and steam.

3.1.6.3 Post-Combustion NOx Control System

The exhaust gas cooling system worked well but some condensed water entered the GAC adsorber. The additional knockout pot was installed; however, a more efficient separator should be used to reduce the amount of condensed water entering the adsorber.

The postcombustion NOx control system was all manually controlled. For commercial operation, it is necessary to install an automatic control system for postcombustion NOx control.

3.2 Estimating System Capital and Operating Costs

3.2.1 Assumption for Cost Estimation

Under the previous California Energy Commission project awarded to SMUD (Grant Number: PNG-07-003) CHA performed the field testing as SMUD's subcontractor to remove H₂S, siloxanes, and hydrocarbons from biogas produced by Sacramento Municipal Waste Water Treatment Plant. Based on field test results, CHA estimated that the carbon reactivation cost using a 100 lb/h mobile microwave unit to support about 100 sites. The cost of supplying reactivated carbon for biogas cleanup was estimated at \$0.70 per pound of reactivated carbon.

CHA has demonstrated the operational feasibility of the pre- and post-combustion NOx control with microwave energy at the CleanWorld BioDigester site. The microwave technology for producing hydrogen from biogas for pre-combustion NOx control was also demonstrated. The cost analysis was based on the actual expenses for the field-testing.

CHA has conducted a field demonstration of the pre- and postcombustion microwave NOx control system using a 190 kW IC engine. But a 500 kW biogas IC engine represents the average

engine for dairy, landfill and food digesters. As a result, a 500 kW IC biogas engine was chosen for estimating capital and operation costs for pre- and post-combustion NO_x control.

The capital and operating costs were estimated based on the assumptions listed below:

- The maintenance costs for the biogas engine were not included since these costs are independent of the NO_x control system. These costs include the engine rebuilding, oil changes, and biogas flaring when the engine is not operable.
- Costs for the annual maintenance and material supplies including catalyst replacement are taken as 5% of the capital cost of the precombustion NO_x control system.
- Researchers assumed the useful life of the major equipment to be 15 years.
- The research team used 15-year straight-line depreciation for money cost and hence the present worth method including the interest rate was not used.
- The team assumed annual operating time was 300 days.
- The carbon replacement cost was assumed at \$0.70/lb by reactivating saturated GAC in the central microwave reactivation facility.

3.2.2 Design Basis and Process Description

Based on test data and from biogas engine at CleanWorld, CHA has developed the design basis for pre- and postcombustion NO_x control for 500 kW. As mentioned before, the research team conducted the postcombustion NO_x control test by running the engine at 100 kW without operating SCR. The average engine exhaust NO_x concentration at 15% O₂ was 102 ppm. The exhaust gas and biogas flow rate for 500 kW engines are 5 times greater than the average flow rates of exhaust and biogas at 100 kW during post-combustion NO_x control tests using two GAC beds in series. The average CH₄ concentration of biogas during tests was 60%. The design basis for H₂ production was estimated based on the lab and field test results of microwave steam reforming. Table 8 presents the design basis for the pre- and post-combustion NO_x control system for a 500 kW biogas engine. Using Table 8, CHA developed a (PFD) that is presented in Figure 35.

Table 8: Design Basis for 500 KW Biogas Engine

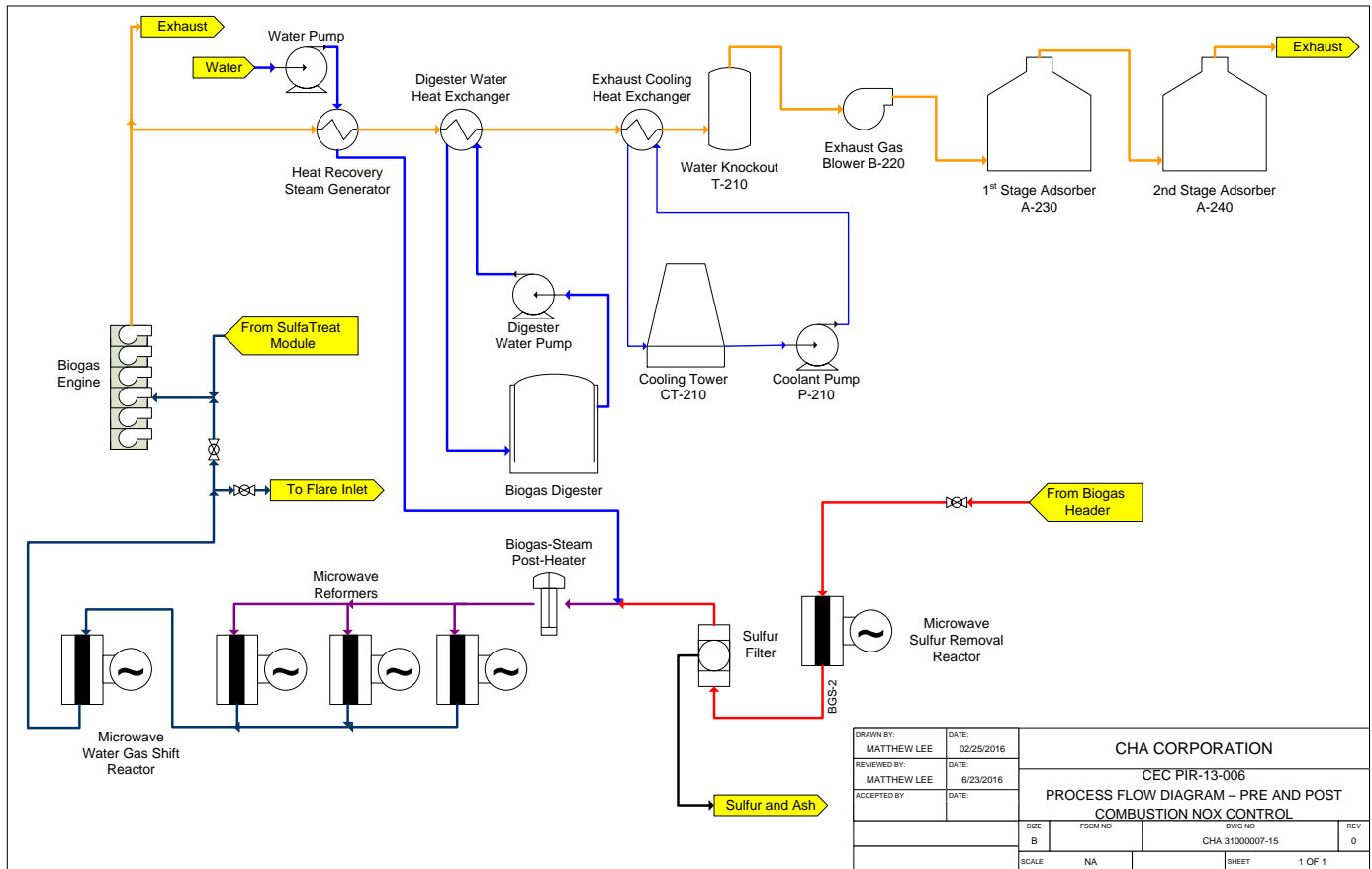
Component	Concentration	Flow Rate
Methane (CH ₄)	60.0%	90 cfm
Carbon dioxide (CO ₂)	40.0%	60 cfm
Inlet biogas to engine		150 cfm
Microwave Steam Reformer		
Biogas, cfm		7.0 cfm
CH ₄ conversion	70%	
H ₂ S removal efficiency	100%	
CH ₄ flow into the reformer		4.2 cfm
Steam flow to the reformer		40 lbs./h
Steam consumed		17.7 lbs./h
Reformer dry outlet gas		18.3 cfm
Hydrogen (H ₂) produced		11.8 cfm

Steam outlet from the reformer		22.3 lbs./h
H ₂ in CH ₄ of biogas	13.1%	
Engine Inlet		
CH ₄		91.3 cfm
CO ₂		62.8 cfm
H ₂		11.8 cfm
Stoichiometric air		897 cfm
Excess air		491 cfm
Total inlet air		1,388 cfm
Total inlet gas to engine		1,551 cfm
Engine Outlet		
Nitrogen (N ₂)	81.2%	1,097 cfm
Oxygen (O ₂)	7.6%	103cfm
CO ₂	11.2%	151 cfm
Total dry outlet gas from engine		1,351 cfm
NOx concentration of engine outlet at 15% O ₂	102 ppm	
NOx produced by engine		7.53 tons/y
NOx removed		7.16 tons/y
NOx emission at 15% O ₂	5 ppm	0.37 tons/y
GAC regeneration		79.32 tons/y

The biogas generated in an anaerobic digester will typically pass through a primary H₂S removal scrubber to reduce the H₂S concentration. The secondary H₂S filter removes H₂S content below 50 ppm. The microwave process takes a side stream of this scrubbed biogas, which enters the microwave H₂S removal reactor. A small amount of air will enter the microwave reactor for H₂S removal. This reactor contains GAC, which catalyzes the reaction of H₂S with the O₂ using microwave energy. The H₂S-free biogas enters the microwave reformer, where steam is injected and the gasses react over a mixed bed of nickel catalyst and SiC. The steam is generated and superheated by hot exhaust gas. It is necessary to investigate how hot exhaust could be used to generate superheated steam. The mixture of biogas and steam enters the biogas-steam post heater and is heated to about 1,000°F (537.8°C) and then enters the microwave reformers.

When the average NOx concentration from the second stage adsorber exceeds 5-ppm at 15% O₂ concentration, the first stage adsorber will be replaced with the second stage adsorber and add the adsorber filled with reactivated carbon as the second stage. The adsorber filled with saturated GAC could be transported to the central microwave reactivation facility. The saturated GAC will be reactivated in the microwave reactivation system. The adsorber filled with reactivated GAC will be operated as the second stage adsorber. The SO₂ and VOC in the exhaust will be removed by GAC in the adsorber.

Figure 35: Process Flow Diagram for Pre- and Post-Combustion NO_x Control (500-kW)



CHA Corporation is working to find the investment for building a central microwave reactivation facility to reactivate activated carbon used for removing various air pollutants including NO_x, H₂S, siloxanes, VOCs and other hydrocarbons. Therefore, it is assumed that the central microwave reactivation facility will be available for this cost estimation.

3.2.3 Capital Cost for Pre- and PostCombustion NO_x Control

CHA accumulated expenses purchasing process equipment, reactor fabrications, and supplies for construction of the microwave prototypes. The pre- and postcombustion NO_x control system was constructed under this California Energy Commission project. The microwave prototype that destroys energetic waste generated by the Air Force Research Laboratory at Edwards Air Force Base was also constructed. Also, large amounts of cost data associated with microwave systems during the construction of two microwave scrubbers installed at Vandenberg Air Force Base are on file and available for use. The actual expenses constructing these microwave systems were used to estimate the capital cost of precombustion NO_x control system for 500 kW biogas engine. Based on these cost data, the purchasing costs for major equipment items were determined.

Table 9 presents the costs for major equipment items and installation cost of pre- and postcombustion NOx control for a 500 kW biogas engine. The capital cost for the pre- and postcombustion NOx control system was estimated at \$359,297 (\$718/kW or \$536/Hp) for a 500-kW biogas engine. The capital costs for pre-combustion NOx control and post-control NOx control are \$514/kW and \$204/kW, respectively. The capital cost for pre-combustion NOx control is 2.5 times greater than the post-combustion NOx control.

Table 9: Capital Cost for Pre- and Post-Combustion NOx Control System

Items	Quantity	Unit Cost, \$	Total Cost, \$
Pre-Combustion NOx Control			
6 kW Microwave systems	3	25,440	76,320
3 kW Microwave systems	2	12,000	24,000
Microwave reactors and microwave applicators	5	7,177	35,885
Gas compressor	1	2,580	2,580
Automatic valve	1	900	900
Flow indicator	1	150	150
Pressure transducer	1	145	145
Thermocouples	8	87	696
Steam flow control valve	1	1,143	1,143
Boiler feed pump and motor	1	324	324
Transmitter, microconnector, steam trap	1	1,114	1,114
Timer control system	1	2,000	2,000
Main power panel	1	2,500	2,500
Microwave cooling water system	1	4,300	4,300
System enclosure	1	3,000	3,000
Catalyst	2	1,000	2,000
High temperature gas heater	1	2,482	2,482
Quartz tubes	10	500	5,000
Material supplies for construction	1	2,000	2,000
Total material cost for pre-combustion NOx control			171,409
Construction cost			85,700
Capital cost for pre-combustion NOx control			257,109
Post-Combustion NOx Control			
GAC Adsorber	2	14,000	28,000
Gas handling system including heat exchanger, water knockout, and blower	1	17,218	17,218
Total materials cost for post-combustion NOx control			45,218
Installation including piping			36,170
GAC cost at \$2.6/lb.			20,800
Capital cost for post-combustion NOx control			102,188
Total Capital cost for pre-and post-combustion NOx control system			359,297

3.2.4 Operating and Maintenance Cost for Pre- and Postcombustion NOx Control

The required amount of GAC depends on the amount of NOx that must be removed by the GAC beds. Also, the amount of GAC replacement depends on the GAC NOx adsorption capacity. The adsorber filled with reactivated GAC will be placed as the second-stage adsorber. The labor cost for the post-combustion NOx control was included in GAC replacement cost.

Table 10 presents the annual operating and maintenance (O&M) costs and the NOx removal cost for the pre- and postcombustion NOx control system. The purchasing price for fresh GAC is about \$3.00/lb. Based on the postcombustion NOx control test, the NOx adsorption capacity of first stage GAC was estimated to be 2.14% when the NOx emission reaches 5 ppm at 15% O₂. To keep the average NOx emission of 5 ppm, 79 tons of GAC must be replaced annually. Then, the GAC replacing cost will be \$475,900 if the fresh GAC is used to replace saturated GAC. This high GAC replacement cost will eliminate the possibility of using postcombustion NOx control with GAC. As mentioned above, CHA Corporation is working to find investment to build a central microwave reactivation facility. If GAC is reactivated in the central microwave reactivation facility, the GAC replacement cost will be reduced to \$0.70/lb or \$111,043 annually. CHA used \$0.70/lb for GAC replacement cost for annual operating cost.

Table 10: Operating and Maintenance Cost for Pre- and Postcombustion NOx Control

Items	Annual	NOx Removal Cost
O&M cost		
Labor for 300 hours (one hour per day) at \$55/h	\$16,500	
Overhead, 50% of Loaded labor	\$8,250	
Supplies and maintenance materials at 5% of pre-combustion NOx control capital	\$12,855	
O&M for pre-combustion NOx control	\$37,605	\$6,886/ton
GAC replacement cost	\$111,043	\$65,319/ton
Total O&M	\$148,648	\$20,761/ton
Depreciation	\$23,953	\$3,346/ton
Total cost	\$172,601	\$24,106/ton
Power produced	521 kW	
Power used	37 kW	
Net power produced	484 kW	
Power for sale	3,484,800 kWh	\$0.05/kWh
Income from power sale at \$0.11/kWh	\$383,328	
Income after NOx removal cost	\$163,769,700	
Power used for H ₂ production	31 kW	
Annual H ₂ produced for NOx control	5,097,600 scf	
H ₂ production cost for 1,000 scf	\$10.74/1,000 scf	

The annual O&M cost for the pre- and postcombustion NOx control microwave system is estimated at \$148,648 to meet the CARB NOx emission standard of 5 ppm. Because the replacement of GAC is included in the GAC reactivation cost, the cost for material supplies was taken as 5% of capital cost of the precombustion NOx control system. The power used by the pre- and postcombustion NOx control is assumed to come from power generated and was not included in annual O&M cost. It was assumed that the operator spends one hour for every operating day. The overhead cost was assumed to be 50% of loaded labor cost of \$55/h.

The 15-year straight-line depreciation is \$23,953. Then, total annual cost for NOx removal is \$172,601. Since the amount of NOx removed is 7.16 tons/year based on 300 days of annual operation, the NOx removal cost is \$24,106/ton of NOx. Per conversation with Venk Reddy of SMAQMD, the NOx removal cost by SCR is \$24,500/ton to meet current NOx emission standards of 11 ppm at 15%.

Based on field test data, the research team was assumed that the pre-combustion NOx control system reduces the NOx emission from 102 ppm to 28 ppm. Then, the post-combustion NOx control system must remove the NOx emission from 28 ppm to 5 ppm at 15% O₂. The amount of NOx removed by the post-combustion NOx control system will be 1.7 tons NOx per year. The NOx removal cost by the post-combustion NOx control system is \$65,319/ton, showing that reducing the NOx concentration from 28 ppm to 5 ppm is costly. The major cost for the postcombustion NOx control is the GAC replacement. The amount of GAC replacement is strongly depends on the NOx adsorption capacity of GAC when the NOx emission reaches 5 ppm. The GAC could adsorb NOx up 10% of its weight if the gas is dry and lower temperature.

Also, the NO should be converted into NO₂ to be adsorbed by GAC. CHA will focus on how to increase the NOx adsorption capacity of GAC to reduce the post-combustion NOx removal cost. Because of high GAC cost, saturated GAC should be reactivated onsite or in a central reactivation facility.

The H₂ production cost for the precombustion NOx control was estimated at \$10.74 per 1,000 standard cubic feet (\$4.25/kg). Trucking H₂ to the dairy for the pre-combustion NOx control has been considered by Energix Research, which estimated the cost at \$28.83/1,000 ft³. This clearly demonstrates that the microwave onsite H₂ production is much cheaper than trucking H₂ for the precombustion NOx control.

3.2.5 Use of Postcombustion NOx Control With Two-Stage GAC Beds

The postcombustion NOx control system using two GAC beds in series removes all criteria air pollutants except CO. The GAC removes air pollutants from exhaust as soon as the engine starts and is not poisoned by sulfur components and siloxanes. Because of low capital cost and easy operation, this post-combustion NOx control system will be better for small engines and engines for supplying emergency power. The SCR requires exhaust temperatures greater than 600°F (315.6°C) and is poisoned by sulfur components and siloxanes. Thus, CHA will estimate the NOx removal cost for the postcombustion NOx control with two GAC beds in series.

The capital cost of postcombustion NOx control shown in Table 9 is \$102,188. The main O&M cost is the GAC replacement. Because of low capital cost and easy operation, this post-combustion NOx control with two GAC beds in series is attractive to meet the Rule 1110.2 NOx emission standards of 11 ppm, especially for small biogas engines.

The equation shown in Figure 33 predicts that the NOx emission at 15% O₂ will reach 11 ppm after 287 hours of adsorption time. The NOx adsorption capacity was estimated at 4.51% after 287 hours when the NOx emission reaches 11 ppm at 15% O₂.

The amount of NOx removed from 500 kW engine exhaust to meet the current NOx emission standards will be 6.63 tons annually. It is necessary to reactivate 147 tons of GAC to keep the average NOx emission of 11 ppm at 15% O₂. Assuming the GAC is reactivated in a central microwave reactivation facility, the annual cost of GAC replacement including onsite service was estimated at \$0.70/lb. Then, the annual O&M cost for the post-combustion NOx control is \$31,042/ton of NOx removed. This is more expensive than SCR.

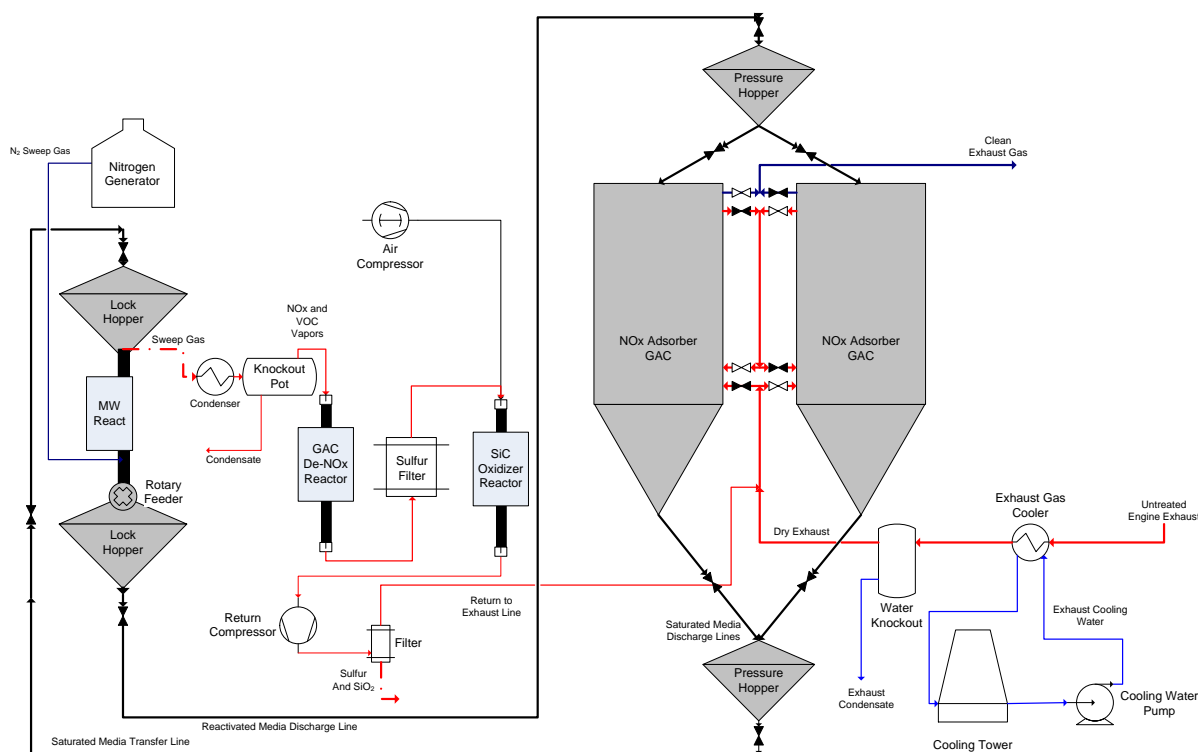
The post-combustion NOx control system could be used to decrease NOx emission from 11 ppm to 5 ppm to meet CARB 2007 NOx emission standards. The amount of NOx removed will be 0.44 tons/year. The additional cost will be \$28,785 or \$65,420/ton assuming saturated GAC is reactivated in a central microwave reactivation facility.

3.2.6 Integrated Postcombustion NO_x Control System with Microwave Reactivation

The GAC replacement cost is a major O&M cost for the post-combustion NO_x control using GAC-bed adsorber. To reduce the GAC replacement cost, the microwave reactivation system may be integrated into the post-combustion NO_x control system.

Figure 36 presents the PFD for the integrated post-combustion NO_x control system with the microwave reactivation. The microwave reactivation system is integrated with the post-combustion NO_x control to reactivate NO_x and VOC saturated GAC continually. Two NO_x adsorbers are located near the microwave reactivation reactor. One of two adsorbers is operated to remove NO_x and VOCs while GAC in the other adsorber is reactivated. Raw engine exhaust is cooled in a heat exchanger and passed through a water knockout to eliminate moisture. The dried exhaust is passed through the adsorber removing NO_x and VOCs before being discharged into the atmosphere. When the carbon in the first adsorber becomes saturated, the exhaust gas is directed to the second adsorber. The saturated adsorber is then bypassed so that exhaust only passes through the second adsorber charged with reactivated GAC. Saturated carbon is conveyed to the lock hopper above the microwave reactivation unit.

Figure 36: PFD for Integrated Postcombustion NO_x Control with Microwave Reactivation



It is essential to keep O₂ out of the microwave reactivator to prevent the carbon from combusting. Both hoppers above and below microwave reactivator are purged with N₂. As microwave energy is applied to saturated carbon, the contaminants are released and enter the

N₂ sweep gas stream leaving the reactor. The newly reactivated carbon is stored in the lower hopper to cool before it is conveyed back into the adsorber and the adsorber is then reopened to the exhaust stream. A star valve below the microwave reactivator controls the carbon flow rate.

The contaminant-laden sweep gas leaving the reactor is dried by a condenser and knockout pot, then fed into the microwave De-NO_x and oxidation unit. The NO_x reacts with carbon in the De-NO_x reactor by microwaves to produce N₂ and CO₂. The NO_x-free gas flows into the microwave oxidizer. Adding a small amount of air, VOCs are oxidized in the microwave oxidizer charged with silicon carbide.

CHA used a radial adsorber to capture the exhaust from the airplane painting shop to capture solvent vapor. The radial adsorber had much lower superficial gas velocity and GAC adsorbed much more solvent. Thus, the radial adsorber will be used to capture NO_x and VOCs in exhaust to increase the adsorption capacity of GAC. Table 11 presents the costs for major equipment items and installation cost of the integrated post-combustion NO_x control with microwave reactivation.

Adding fresh GAC purchasing to the installed cost provides the capital cost of \$285,159. This is equivalent to \$570/kW which is lower than the capital cost for the pre- and postcombustion NO_x control system.

Table 12 presents the O&M cost for this integrated postcombustion NO_x control. The annual O&M cost was estimated at \$48,170. The cost for material supplies was taken as 5% of installed equipment cost. The cost for the power used by the postcombustion NO_x control with microwave reactivation is \$14,400 at \$0.1/kWh. It was assumed that the operator spends one hour for every operating day. The overhead cost was assumed to be 50% of loaded labor cost of \$55/h.

The 15-year straight line depreciation of installed equipment is \$17,624. Then, the total annual cost for NO_x removal is \$65,794. Since the amount of NO_x removed is 7.16 tons/year based on 300 days of annual operation, the NO_x removal cost is \$9,189/ton of NO_x. The NO_x removal cost for the integrated post-combustion with microwave reactivation is much cheaper than the conventional SCR system.

The NO_x and VOC saturated GAC is reactivated by microwave system continually to meet the CARB 2007 NO_x emission standards of 5 ppm. For 24-hours operation, 3.6 million kWh are produced. The NO_x removal cost per power produced is \$0.018/kWh. This NO_x control cost is much cheaper than the pre- and postcombustion NO_x control with carbon replacement.

Table 11: Capital Cost of Integrated Post-Combustion NOx Control and Microwave Reactivation

Description	Quantity	Unit Cost	Cost
Microwave Generator and Reactor			
6kW Microwave Power Supply and Remote Magnetron	1	\$ 25,440	\$ 25,440
3kW Microwave Generator set - complete	2	\$ 12,000	\$ 24,000
Microwave reactors and applicators	3	\$ 7,177	\$ 21,531
Rotary Feeder	1	\$ 1,200	\$ 1,200
Variable Speed Rotary Feeder Drive	1	\$ 450	\$ 450
Air Compressor	1	\$ 300	\$ 300
Flow Meter	4	\$ 500	\$ 2,000
Pressure Gauge	2	\$ 200	\$ 400
Nitrogen Generator	1	\$ 5,000	\$ 5,000
Condensor System			\$ -
1st Stage Condensor	1	\$ 1,500	\$ 1,500
40 gal. Stainless Steel Knockout Pit	1	\$ 1,900	\$ 1,900
Level Indicators	2	\$ 400	\$ 800
Pressure Transducers	2	\$ 200	\$ 400
Teflon Diaphragm Compressor	1	\$ 2,300	\$ 2,300
Thermocouples	7	\$ 100	\$ 700
Recirculating Chiller	1	\$ 4,500	\$ 4,500
Gas Cooling System	1	\$ 17,218	\$ 17,218
Electrical			\$ -
Panel and Breakers	2	\$ 400	\$ 800
Main Disconnect	1	\$ 1,000	\$ 1,000
Conduit/Wires	1	\$ 3,000	\$ 3,000
Hoppers			\$ -
Adsorbers	2	\$ 14,000	\$ 28,000
Feed	1	\$ 1,200	\$ 1,200
Product	1	\$ 1,200	\$ 1,200
Level Indicators	2	\$ 400	\$ 800
Valves	2	\$ 1,300	\$ 2,600
Conveyor	1	\$ 4,000	\$ 4,000
Structure			\$ -
Instrument Enclosure	1	\$ 4,000	\$ 4,000
Skid	1	\$ 5,000	\$ 5,000
PLC (Includes motor starters and programming)	1	\$ 15,000	\$ 15,000
Total Equipment Cost			\$ 176,239
Construction and Installation			\$ 88,120
GAC at \$2.6/lb			\$ 20,800
Total Installed Cost or Capital Cost			\$ 285,159

Table 12: O&M Cost of Integrated Post-Combustion NOx Control & Microwave Reactivation

Items	Annual	NOx Removal Cost
O&M cost		
Labor for 300 hours (one hour per day) at \$55/h	\$16,500	
Overhead, 50% of Loaded labor	\$8,250	
Supplies and maintenance materials at 5% of pre-combustion NOx control capital	\$8,812	
Electricity cost at \$0.1/kWh	\$14,400	
GAC supplement to make up loss	\$208	
Total O&M	\$48,170	\$6,728/ton
Depreciation	\$17,624	\$2,461/ton
Total cost	\$65,794	\$9,189/ton
Power for sale for 300 days	3,600,000 kWh	\$0.018/kWh

3.2.7 Comparison

Table 13 presents the comparison of existing postcombustion NOx removal technologies¹⁰ (SCR and NOx Tech) with microwave pre- and postcombustion NOx control, postcombustion NOx control with two carbon beds, and integrated post-combustion NOx control with microwave reactivation.

As shown in this table, the cost of NOx removal using the microwave pre- and postcombustion approach tested in this project is comparable to both SCR and NOx Tech. CHA microwave system for pre- and postcombustion and integrated postcombustion NOx Control with microwave reactivation will meet Rule 1110.2 and CARB 2007 NOx emission standards. The SCR and NOx Tech may not meet CARB 2007 NOx emission standards.

Table 13 shows that the postcombustion NOx control with microwave reactivation is the most cost effective method of NOx control. During the field testing, NOx-saturated GAC was reactivated using the microwave reactivation system that was located at the SATS BioDigester site. Under the previous ICAT project CHA demonstrated the integrated postcombustion NOx control system at the former McClellan Air Force Base to remove NOx from diesel engine exhaust. Thus, CHA is ready to install the integrated postcombustion NOx control with microwave reactivation.

¹⁰ CARB Board Meeting, July 9, 2010, Agenda No. 25

Table 13: Cost Effectiveness for Pre- and Postcombustion NOx Removal Technologies

Technology	\$/ton NOx removed	\$/1000 ft3 Biogas Consumed	Cents/kWh Power Produced	Pollution Standards Achieved
CHA Microwave System for Pre- and Post-Combustion	24,100	2.66	4.8	Rule 1110.2, CARB 2007
Post-Combustion NOx Control with GAC Beds	31,000	3.21	5.8	Rule 1110.2
CHA Integrated Post-Combustion NOx Control with Microwave Reactivation	9,200	1.02	1.8	Rule 1110.2, CARB 2007
SCR +Oxidation Catalyst, Post-Combustion	27,000	2.8	5.0	Rule 1110.2
NOx Tech, Post-Combustion	25,000	2.59	4.7	Rule 1110.2

As shown in Table 13, the cost of meeting CARB 2007 NOx standards is \$2.66 per 1,000 ft³ of biogas consumed for the microwave pre- and postcombustion NOx control. This cost is reduced to \$1.02 for the integrated postcombustion NOx control with microwave reactivation. In contrast, the cost for SCR to meet Rule 1110.2 NOx emission standards is \$2.80 per 1,000 ft³ biogas consumed that is about the same as the pre- and post-combustion NOx control. The use of integrated postcombustion NOx control with microwave reactivation could save \$1.78 per 1,000 ft³ of biogas consumed and meet CARB 2007 NOx emission standards.

The cost of meeting CARB 2007 NOx emission standards is 1.8 cents per kWh electricity produced from biogas. In contrast the cost of meeting the less strict Rule 1110.2 with existing SCR is 5.0 cents per kWh electricity generated from biogas. Using onsite microwave reactivation saves 3.2 cents per kWh electricity generated from biogas. The cost of meeting the CARB 2007 NOx emission standards is lower than the special feed-in-tariff of 6 to 9 cents per kWh.

3.3 Technology/Knowledge Transfer Activities

The effective means of distributing results from this California Energy Commission-funded program to the public is through presentations at topical and related technical conferences as well as publications. It is very important for potential end users and regulatory agencies to be aware of pre- and postcombustion NOx control microwave technology and field-testing results.

To pursue the commercialization of pre- and post- combustion NOx control, CHA staff members identified engine companies, biogas project developers, and regulatory agencies. Then, they prepared the presentation of the field test results and advantages of microwave technology. Below is a list of engine companies, project developers, and regulatory agencies that will be interested in field-testing results.

3.3.1 Engine Companies

The following is a list of biogas-powered engine companies that the CHA Corporation would like to contact for presenting the field test results.

- 2G Cenergy
- Martine Machinery
- Jenbacher-GE
- Caterpillar

CHA submitted the field test report to Tony Dawson, Service Director of 2G Cenergy. The proposal for conducting the field-testing for the online destruction of hydrogen sulfide and siloxanes was also submitted. Dawson transferred the report and proposal to their R&D Director.

CHA will contact other engine companies listed above and present the field test results.

3.3.2 Project Developers

To commercialize the NOx control technology field-tested under this California Energy Commission project, CHA staff is contacting biogas project developers and will present the field-testing results and advantages of microwave-based NOx control technology. The following provides a summary of CHA's activities.

Glenbrooks Investment Holding owns 75% of Sacramento BioDigester facility. CleanWorld transferred the operation of this digester facility to Glenbrooks. CHA completed the field-testing of pre- and post-combustion NOx control at this site. Glenbrooks must operate the post-combustion NOx control system including two carbon beds to meet the NOx emission standards if they operate the biogas engine. CHA submitted the proposal to Glenbrooks, assisting the operation of the post-combustion NOx control system at SATS biodigester site including reactivation of saturated GAC. CHA also proposed the reactivation of GAC used for their Bio-CNG facility.

Glenbrooks has chosen ES Engineering to operate SATS biodigester facility. CleanWorld turned over the operation of the SATS biodigester facility to ES Engineering by the end of March 2017 but still owns 25% of the facility. CleanWorld is also working on designing larger biodigester systems for food wastes. Under this California Energy Commission project the CHA staff found that microwave energy combined with GAC could destroy biogas impurities including H₂S and siloxanes. CHA is working with CleanWorld to find the funds for field testing of this microwave system. CHA submitted a proposal to Cal SEED to conduct the field testing of microwave biogas cleaning system at the SATS biodigester facility with CleanWorld. CleanWorld is working with ES Engineering for the design of larger biodigester facility.

SMUD has supported CHA Corp since 1998 for the development of microwave-based NOx control technology, and is their partner for this California Energy Commission project. Dr. Val

Tiangco of SMUD will continue assisting CHA Corp to contact the dairy digesters and food waste/organic waste digesters including Mass Energy Works.

3.3.3 Regulatory Agencies

The field testing results were presented on March 24, 2017 to SMAQMD, CARB, and SMUD. The meeting was held at SMAQMD Office and attendees were listed below.

SMAQMD: Brian Krebs - Program Coordinator, the Construction Permit to Clean World
Venk Reddy - Worked on the construction permit to Clean World
Jorje Deguzman

CARB: Tung Le - Manager of the Stationary Source Division
Mei Fong - In charge of biogas

SMUD: Val Tiangco - Manager of Biofuel
Dagoberto Calamateo
Reynaldo
Rick Wiesner - Retired patent attorney

Clean World: Josh Rapport, -Vice President

CHA Corp: Chang Yul Cha - President and Project Manager
Bill Burr -Lab Director
Matthew Lee - Research Engineer

Mei Fong arrived early and asked about CHA's NO_x control technology. Dr. Cha described a summary of the technology before the meeting officially began. He opened the meeting by welcoming attendees and introducing himself. He acknowledged California Energy Commission for funding the project and Clean World for supporting the field-testing. He then described the project's objectives in demonstrating the NO_x control technology, emission goal, and scope. Dr. Cha presented the lab test results for H₂S destruction and steam reforming. Dr. Josh Rapport presented a brief history of CleanWorld, their facility at the SATS, and how their facility turns food waste into biogas. Dr. Cha then presented CHA Corp's installation of equipment at SATS and field testing results including the source testing of CleanWorld's engine by Blue Sky Environmental, Inc. A NO_x removal cost comparison was presented by him, describing the most cost-effective solution. Dr. Cha concluded by presenting the relationship with Technikon to build a 300 lb/h microwave carbon reactivation unit, and project benefits to California.

Rick Wiesner presented the previous microwave projects CHA Corp field tested with SMUD's support. Brian Krebs asked about the discrepancy in Blue Sky Environmental report. Carbon monoxide (CO) from SCR was reported at 62 ppm and 0.37 g/BHp-hr while CO emission from SCR plus carbon beds were reported as 65 ppm and 0.26 g/BHp-hr. Higher CO concentration in ppm should result in higher CO in g/BHp-hr. Dr. Cha said that these were the numbers

provided by Blue Sky Environmental report, and the CHA Corporation will review these numbers and seek clarification.

Jorje Deguzman mentioned how automobile paint shops could be a potential customer for CHA's reactivated carbon. He asked many questions regarding pre-combustion NOx control test.

Tung Le asked about the CARB 2007 NOx emission standards of 5 ppm. Other attendees said that they have not heard of these standards. He suggested that NOx adsorption with activated carbon would be useful for emergency generators such as those used in hospitals. Emission standards for emergency generators are not as strict as continuous generators, but are only allowed a limited amount of testing hours per year at their highest emission rates. Using activated carbon to adsorb NOx would allow for longer testing if needed, since engine emissions during tests would be reduced by the carbon. In contrast with SCR, carbon adsorption is simpler with no moving parts and is always active, not needing to start and stop with the engine. He told CHA Corp that he would like to follow up the future development of microwave NOx removal technology. All attendees showed strong interests in the microwave technology for pre- and post-combustion NOx control.

3.3.4 Project Final Meeting

The project final meeting was held March 29 at the California Energy Commission office to present project findings, conclusions, and recommendations. Attendees are listed below:

California Energy Commission:	Chuck Gentry - Agreement Manager, Mechanical Engineer
	Ghasem Edalati - former Agreement Manager
	Mike Kane - Mechanical Manager
	Kevin Uy - Mechanical Engineer
	Timothy Smith - Mechanical Engineer
West Biofuel:	Matthew Summers - Vice President
CHA Corporation:	Chang Yul Cha - President, Project Manager
	Bill Burr - Lab Director
	Matthew Lee - Research Engineer

Chuck Gentry opened the meeting by stating that the goal of the project was to conduct the field demonstration of the integrated microwave technology for pre- and post-combustion NOx control.

Dr. Cha presented the lab and field test results, NOx removal cost, near-term commercial plan, and meeting with SMAQMD and ARB. The post-combustion NOx control with microwave reactivation was the most cost effective NOx removal technology. He stated that the pre- and post-combustion NOx control met CARB 2007 NOx emission standards. Furthermore, he compared pre- and post-combustion NOx control test results with specific target goals. Then,

he presented the conclusions, recommendations, and project benefits to California. Dr. Matt Summers asked about the temperature of exhaust entering the carbon adsorber. Also, he asked about the NO_x removal efficiency with carbon beds.

3.3.5 Conferences

CHA submitted an abstract to the 10th Waste Conversion Technology Conference & Trade Show to present the field test results. This conference will be held August 21-23, 2017 at San Diego, California. Staff will consider presenting the field test result to other conferences including International Biomass Conference & Expo and Chemical Engineering 2017. Because of travel expenses, staff will continue to check any conference that will be held in California.

3.3.6 Publications and Journals

Because of travel expenses, the distribution of field test results obtained under this California Energy Commission project to the public is through publications. CHA will prepare an abstract and paper for the field test results and submit to journals. Also, CHA will prepare the paper to publish lab-test results. The following journals will be considered for submitting the papers:

- Journal of Environmental Sciences – Elsevier- Field test result of pre-and post-combustion NO_x control
- American Society of Agricultural and Biological Engineers – Field test results
- Chemical Engineering – Microwave steam reforming
- Carbon-Elsevier – International journal founded in conjunction with the American Carbon Society – Field test result from post-combustion NO_x control.

3.4 Production Readiness Plan

3.4.1 Commercialization Opportunity

CleanWorld's AD system is one of many AD designs that share the same problem of air emission control where power generation is the end-use of the biogas produced. In addition to power generation, CleanWorld separates CH₄ from biogas to produce CNG that is pipelined to the filling station next door. California presently has 15 AD dairy systems operational plus a growing number of food waste AD systems. These numbers are only going to increase because of AB 32 that regulates reduction in CH₄ emissions from farming and landfills. SMUD estimates that about 1,400 dairy operations in California must install AD systems within the next five years.

Landfill gas cleaning for either power generation or pipeline gas is also a growing market and is termed renewable natural gas (RNG). The California based Renewable Natural Gas Coalition recently reported: "There are more than 53 RNG projects in the U.S., 43 of which inject into the natural gas pipeline system. These projects convert a portion of the more than 70 million tons of organic waste generated per year in the U.S. into ultra-clean compressed natural gas and liquefied natural gas transportation fuel and renewable heat and power."

Landfill biogases and AD biogases also can utilize AC to remove H₂S and siloxanes in the cleaning process and secondarily remove NO_x from the power production engine exhaust. Both CHA and TEC developed microwave technology and equipment. These co-developed microwave equipment can be used to clean both the source gas stream as well as the engine exhaust.

The field testing results clearly show that the post-combustion NO_x control demonstrated under this project is the best NO_x control to meet the Rule 1110.2 soon and CARB 2007 NO_x emission standards in the future. The onsite or central microwave regeneration will be critical to this post-combustion NO_x control. CHA and TEC are starting to prepare a commercialization plan to build a central microwave regeneration facility.

3.4.2 Present Operational Concept

The SATS BioDigester site is a strategic location for continued testing and refinement of equipment, as well as development of the market service business revenue. It supplies a source of GAC that requires regeneration and minimizes the logistics of testing since it is less than 30 minutes from the CHA Corporation offices.

Two GAC adsorbers are installed at the SATS digester facility to capture NO_x from the engine. The microwave mobile unit is also installed at the site to reactivate saturated GAC. The mobile unit has a limit of 50 lbs/h of reactivation capacity and requires manpower to operate. The adsorber installed at the SATS biodigester site containing 1600 pounds of GAC would require (4) eight hour days of processing time. Each adsorber would take about two months to saturate if the engine operates continually. So basically, the reactivation unit would operate one week per month. The off-production weeks could be used to modify the system or testing of other AC from other sites. It is doubtful in the short term the biogas engine at SATS would be operated around the clock, so field reactivation might more likely be less often. In addition to GAC used for NO_x control, SATS biodigester site uses six GAC beds, each contains about 1,100 lbs. The GAC each bed is required to be replaced every six months, indicating that about 1,100 lbs of GAC could be reactivated per month.

3.4.3 Development Efforts Needed

The existing mobile reactivation unit originally could process 100 lbs/h but one power supply malfunctioned and system was modified to operate on one quartz tube at 50 lbs/h. The feeding of AC through the quartz tube system has had plugging problems and needs addressing. The goals of a reactivation system design would be: a) to have consistent quality output, b) have system operate unattended except for total change out of GAC and c) have design that can be economically scaled up to process GAC at 300 lbs or more per hour.

The initial team meeting led CHA to believe that the feeder and activation chamber area needs to be redesigned for optimize throughput and power requirements. Multiple ideas have been suggested and staff will use a systematic method to decide on the approaches that would be the most likely to be successful in the field. Initial designs would be built and tested in the CHA lab and then taken to the SATS biodigester site to shake out.

3.5.4 Preliminary Commercialization Concept

The SATS digester site allows CHA to do a proof of concept project on Exhaust Gas cleaning using AC. Once the NO_x removal process is proven to the satisfaction of CARB, it is likely to become the BACT approach. BACT designation would then give CHA a virtual monopoly for enough time to establish a significant market position. CHA and Technikon (TEC) agreed to form a new company (EVVO Systems) to commercialize CHA's technology for microwave reactivation of AC. EVVO would market the CHA NO_x control technology to new and existing AD system suppliers as lower cost alternative to replace the need for expensive SCR control systems. The EVVO NO_x control system would include: AC totes, positive pressure fan system, gas chiller, piping system and control system.

A second EVVO revenue opportunity would be to develop an AC supply service for reactivation and provide replacement AC totes for customers whose filter media has become saturated. Depending on the customer density and distance, this could become a hub and spoke service area with a centralized process plant. This plant would initially need a supply of new AC to cover downtimes but should be able to process saturated AC for 25% or less than the cost of new AC.

It is likely that CHA would start with a standard 2,000 lb metal tote like the ones used at the CleanWorld's SATS digester site. There would be minimal on site handling fees as the saturated AC totes would be picked up as a unit and replaced with a packaged unit containing reactivated AC.

Starting with one 300 ton per hour microwave reactivation system operating 5 days per week, it is feasible that this single plant unit could reactivate the saturated generator NO_x cleaning AC from about 30 AD plants of similar size (190 kw gensets).

New AC cost per pound is more than \$2 and using the assumption that the market would support \$1.50 per pound for regeneration of AC; each 300 lbs/h microwave reactivation plant would generate \$2.5 million in year of revenue. Operational costs will need to be calculated once the system is designed and optimized.

3.5.5 Business Planning Phase

TEC will lead development and assessment of the EVVO business plan. CHA will support TEC as needed. The business plan will include the value proposition, market opportunity, the business strategy to capture the market opportunity, competitive threat to EVVO, financial projections and investment needs to execute the business plan.

During the business planning phase, CHA will evaluate the various options to scale up the microwave reactivation reactor design to 300 lbs/h. TEC will assist CHA to select the scaled reactor design. After the microwave reactor design is chosen, CHA will start to build a model of the scaled microwave reactivation system in its laboratory before constructing the 300 lbs/h microwave regeneration facility at the SATS biodigester site.

Both CHA and TEC will cover its own costs during the Business Planning Phase and share equally any out-of-pocket expenses required to complete the Business Planning Phase, provided these costs are mutually agreed.

At the end of the Business Planning Phase, CHA and TEC will assess the business plan. If both parties agree the plan is an attractive business proposal, then EVVO will be formally established and fundraising for EVVO will commence.

Provided both parties agree that the Business Planning Phase was successfully completed, CHA will lead efforts to raise sufficient investment capital to execute the first 12-18 months of the business plan.

3.4.6 Timetable

CHA and TEC intend to implement the activities and structure set out above as quickly as reasonably as practical. The target timetable contemplated is as follows:

- By May1, 2017: Complete Business Planning Phase
- By June 1, 2017: Establish EVVO and start fund raising provided Business Planning Phase is successfully completed
- By October 1, 2017: Complete fund raising for EVVO

CHAPTER 4:

Conclusions and Recommendations

4.1 Results Compared to Goals

4.1.1 Goal of Pre-Combustion NOx control

The overall goal of pre-combustion NOx control was to demonstrate HALO which would be applicable to biogas engines and could significantly reduce NOx formation. The specific goals were: (1) H₂S concentration of microwave treated biogas < 0.1-ppm, (2) bio methane conversion to H₂ > 70%, (3) NOx reduction by HALO > 70%.

The H₂S removal tests were conducted at 109 and 164 L/min (3.8-5.8 cfm) biogas that contains 20 ppm H₂S. The H₂S in biogas was destroyed and was not detected with Dragger tubes. Thus, the specific goal for H₂S removal was achieved. The microwave H₂S removal test must be conducted using biogas containing higher H₂S concentration to confirm this result.

The steam reforming tests were conducted with various flow rates using biogas consisting of 47.2% CH₄ and 52.8% CO₂. The CH₄ conversions were 78% and 74% for the biogas flow rate of 25 and 30 L/min, respectively. When biogas flow increased to 40 L/min, the CH₄ conversion decreased to 64%. The CH₄ conversions were comparable to the lab-steam reforming test result. However, the H₂ production rates were much lower than the lab result because of lower CH₄ concentration in the biogas. At least 70 L/min H₂ production is needed for the pre-combustion NOx control test. The CH₄ concentration of biogas was 47.2% but the lab-simulated biogas had 66.6% CH₄ concentration. To increase the H₂ production rate, CNG produced by CleanWorld had to be used.

The CH₄ conversion decreased from 75% to 44% but the H₂ production increased from 37 L/min to 80 L/min as CNG flow rate increased from 14 L/min to 41 L/min. The CH₄ conversions and H₂ productions were lower than lab-tests at given CH₄ flow rates. The specific goal of bio methane conversion was met at the lower flow rate but was not met for the higher flow rate to produce H₂ required for pre-combustion NOx control.

Because CleanWorld was not allowed to change the air/fuel ratio, the pre-combustion NOx control tests were run for three days with the engine technician from Western Energy. The NOx emission decreased as the O₂ concentration of exhaust increased. The lowest NOx emission of 28-35 ppm at 15% O₂ was obtained when exhaust O₂ concentration was 7.6-8.2% (air/fuel ratio = 1.57-1.64). However, the engine was not stable with this air/fuel ratio. The engine ran very stable with the air/fuel ratio of 1.47 with 2.6-cfm H₂ injection. The NOx emission with stable engine operation was 67 ppm at 15% O₂, which was a 72% reduction from 239 ppm before the air/fuel ratio increased. Thus, the specific goal for NOx reduction by HALO was met with stable engine operation.

4.1.2 Goal of Post-Combustion NOx Control

The goal of the integrated system of pre- and post-combustion NOx control was to meet the Rule 1110.2 (average NOx emission of 11-ppm) soon and ultimately meet CARB 2007 standards (average 5-ppm NOx emission). The specific goals of the post-combustion NOx control were to achieve the average NOx less than 5-ppm and SO₂ and VOC removal efficiency greater than 90% with no SCR.

The post-combustion NOx control tests were conducted for 5 months whenever the engine ran without operational problems. The NOx adsorption test was performed with SCR and one GAC bed at 190-kW for 61 hours. Then, the post-combustion NOx control tests were run with two GAC beds in series without SCR for 3 months.

After 136 hours of NOx adsorption with two GAC beds, the average NOx emission reached 5-ppm at 15% O₂. All concentration data given below are values corrected to 15% oxygen. During the post-combustion NOx control tests, the NOx emission was lower than 5-ppm. When the average NOx emission from the second bed reached 5-ppm the first GAC bed had adsorbed 35.8 pounds of NOx and the second GAC bed had adsorbed 16.2 pounds of NOx. Therefore, NOx adsorption capacity of the first GAC bed was 2.14% when the NOx emission from the second bed reached 5-ppm.

Through the field testing period the average NOx emission did not exceed 5 ppm to confirm that pre- and post-combustion would meet not only the Rule 1110.2 but also CARB 2007 NOx emission standards.

Blue Sky Environmental, Inc. performed the source test to determine compliance of the 190-kW biogas engine in respect to SMAQMD request. Source testing was performed for the engine SCR emissions and engine SCR plus Carbon Bed emissions. Average NOx emissions from the Engine SCR were 22.3 ppm which did not meet the emission standard of 11 ppm. The NOx emission from the engine SCR plus carbon-bed was 0.4 ppm which met the emission standard of 11 ppm. Both engine SCR and engine SCR plus carbon bed met the CO emission standard of 250 ppm. Hydrocarbons greater than C₂ (as ethane) were not found in the sample taken from both outlets. Thus, VOCs were not found in both emissions. Ammonia emission from the Engine SCR was 11.9 ppm which exceeded the emission standard of 11 ppm. However, ammonia emission of Engine plus Carbon Bed was 0.31 ppm that met the emission standard. The source testing results clearly show that engine SCR plus carbon bed should be used to meet NOx and ammonia emission standards. The GAC bed adsorbed ammonia very well and could be used to remove ammonia from SCR exhaust.

The concentration of SO₂ in the outlet from the second stage adsorber was monitored hourly. No SO₂ was detected in the adsorber outlet. When the saturated GAC was reactivated, the THC concentration of the sweep gas was 1,900-2,000 ppm. But hydrocarbons greater than C₂ were not found in the sample taken from the GAC adsorber outlet. This confirms that all VOCs in exhaust were adsorbed in the GAC bed.

The postcombustion NOx control test demonstrated the feasibilities listed:

- The postcombustion NOx control with two GAC beds in series with or without the pre-combustion NOx control will meet the Rule 1110.2 (average NOx emission of 11-ppm) and can also meet CARB 2007 standards (average 5-ppm NOx emission).
- The postcombustion NOx control with two GAC beds in series can be used with existing SCR to meet the current NOx emission standards of Rule 1110.2 and CARB 2007 NOx emission standards in the future.
- The precombustion NOx control increases the GAC life time to meet the Rule 1110.2 and CARB 2007 NOx emission standards and reduces the operating cost for NOx treatment.
- The GAC bed can be used to remove ammonia generated from SCR to meet the ammonia emission standards of 11-ppm.
- The postcombustion NOx control with two GAC beds in series has lower capital cost but high operating cost. Onsite or central microwave regeneration should significantly reduce the GAC replacement cost.
- The GAC adsorption capacity of the first bed was 2.14% when the average NOx emission from the second bed reached 5-ppm and estimated to be 4.5% when the NOx emission reaches 11-ppm.

4.2 Conclusions

The field testing results clearly demonstrated that pre-and post-combustion NOx control will meet not only the Rule 1110.2, but also CARB 2007 NOx emission standards. The following conclusions were drawn from pre-combustion NOx control test data and post-combustion NOx control test data as well as observations during field testing.

- Microwave energy combined with GAC was very effective in destroying H₂S on site and is a very good candidate for removing H₂S and siloxanes from biogas without using adsorbents.
- Microwave steam reforming provided the CH₄ conversion greater than 70% for biogas flow rate lower than 35 L/min. Because of low CH₄ concentration of biogas (<47%), a higher biogas flow rate must be processed to produce the H₂ required for pre-combustion NOx control.
- The microwave reactor design for steam reforming must be changed to reduce the heat loss and to process higher biogas flow rates.
- The CH₄ conversion was greater than 70% for the CNG flow less than 20 L/min but decreased to 45% as the flow rate increased to 40 L/min. The heat loss must be reduced to increase the conversion.
- Microwave steam reforming can be applied for economical onsite H₂ generation from biogas for pre-combustion NOx control and fuel cells.

- Application of HALO is effective for a biogas engine to reduce NOx formation.
- The air/fuel ratio can be increased with stable engine operation by injecting H₂ into the biogas inlet. Greater than 70% of NOx formation was reduced with stable engine operation by injecting H₂ into biogas inlet.
- It would be difficult to reduce the NOx emission to 11-ppm because the H₂ required would be one-third of the CH₄ volume in biogas. Thus, HALO alone may not be economical to meet the Rule 1110.2. Also, HALO alone will not meet CARB 2007 NOx emission standards.
- Post-combustion NOx control using two GAC beds in series was very effective to meet the Rule 1110.2 and CARB 2007 NOx emission standards.
- Two GAC beds in series is also an efficient method to assist existing SCR to meet CARB 2007 NOx emission standards of 5-ppm.
- Reducing superficial gas velocity through the GAC bed increased the NOx removal rate. When the superficial gas velocity was reduced from 25 ft/min to 15 ft/min, the NOx removal rate increased three times (from 1.12 ft³/h to 3.37 ft³/h).
- GAC NOx adsorption capacity was 2.14% when the average NOx emission reached 5-ppm at 15% O₂. Economical GAC reactivation needs to be developed to reduce the operating cost or NOx removal cost.
- GAC beds completely removed ammonia, SO₂, and VOCs from exhaust.
- NOx-saturated GAC was reactivated in the microwave mobile unit and mobile microwave unit could reduce the operating cost of post-combustion NOx control.
- NOx and VOCs released from microwave reactivation of saturated GAC were destroyed in the De-NOx GAC and oxidizer catalytic microwave reactors.
- Integrated post-combustion NOx control with microwave reactivation is the most cost effective NOx control to meet CARB 2007 NOx emission standards.

4.3 Recommendations

The biogas produced in food and manure digesters contains H₂S that must be removed to protect engines and to remove SO₂ emission. The primary H₂S scrubber uses adsorbent containing iron oxide or other sulfur treatment chemicals. The secondary H₂S scrubber uses GAC. The post-combustion NOx control methods such as NSCR and SCR use catalysts that are susceptible to sulfur poisoning and require reliable and efficient pretreatment of the biogas to remove H₂S. The biogas produced from landfill and wastewater treatment contains H₂S and siloxanes. Siloxanes in biogas must also be removed to prevent catalyst poisoning and to protect engines. Cost-effective and complete removal of H₂S and siloxanes is the major barrier for the conventional post-combustion NOx control technologies such as SCR. Sulfur treating media, GAC, and other adsorbents are used to remove H₂S and siloxanes. These media must be replaced with fresh media when saturated. The cost associated with replacing media is a

significant portion of NOx removal cost. As shown in the H₂S removal test results, the microwave combined with GAC is very effective at destroying these impurities onsite and does not produce any harmful waste. Therefore, CHA highly recommends the field-testing of microwave-based biogas cleanup be conducted to determine its economic and technical feasibility.

The post-combustion NOx control using two GAC beds in series has very low capital cost and does not require pre-treatment of biogas to remove H₂S and siloxanes. However, the cost for replacing GAC is a major operating cost. Because fresh GAC is expensive, NOx-saturated GAC must be reactivated and reused. To be economical, NOx-saturated GAC must be reactivated onsite or in a central location. CHA demonstrated the onsite reactivation of NOx-saturated GAC using the mobile microwave unit. Therefore, CHA would like to recommend the economic and market study be performed to reactivate NOx-saturated GAC on a mobile unit or a central facility close to biogas producers.

4.4 Project Benefits for California

4.4.1 Reduction of Criteria Air Emissions

The postcombustion NOx control system using GAC beds removes NOx, SO₂, VOCs, and ammonia from engine exhaust. The capital cost of this post-combustion NOx control system is lower than SCR and other post-combustion control systems. The main challenge is to reactivate used GAC onsite or in a central reactivation facility to reduce the GAC replacement cost. CHA demonstrated the onsite reactivation of used GAC and is preparing for the construction of the 300 lbs/h central reactivation plant. In the microwave reactivation, NOx and SO₂ in the desorbed gas from saturated media are destroyed in the GAC reactor and VOCs and lower hydrocarbons are destroyed in the oxidizer by microwave energy. The GAC saturated with H₂S and siloxanes can also be reactivated in microwave reactivation reactor and H₂S desorbed is destroyed GAC bed by microwave energy. Thus, the microwave reactivation system eliminates all air emissions attributed to biogas and exhaust gas cleanup. This microwave reactivation technology will be a totally contained system and will not have any air emissions.

This microwave-based technology allows CARB 2007 NOx emission standards to be met, making biogas cleaner and more acceptable in populated communities, accomplishing the intent of the regulation. Meeting these emission standards will eliminate 221 pounds of NOx from 1 million cubic feet of biogas used for power generation. Integrated post-combustion NOx control with microwave reactivation is the most cost effective NOx removal technology. The NOx removal cost of this technology is 1.8 cents per kWh power produced, which is lower than the special feed-in-tariff of 6 to 9 cents per kWh.

Existing commercial thermal reactivation systems require a flare to destroy VOCs, siloxanes and H₂S from the reactivation step. The microwave oxidizer could be configured to replace the flare and significantly reduce criteria air emissions from media reactivation. This would have a significant impact in California where air emission regulations typically preclude the use of uncontrolled flares.

In the microwave H_2S destruction reactor prior to the microwave steam reformer, the H_2S was destroyed by microwave energy. The siloxanes can be also destroyed by microwave energy in this GAC reactor. If this technology is scaled up and commercialized, the media for removing H_2S and siloxanes will be replaced by the microwave reactor. Then, the air pollutants generated from the production of media will be eliminated.

Sulfur in the biogas precludes all commercially available post-combustion controls using catalysts without reliable and robust H_2S removal. Removing H_2S and siloxanes from biogas will provide a new technology to significantly reduce VOCs and SO_x emissions from biogas engines to meet the CARB 2007 emission standards and may enable the use of traditional and new post combustion control technologies.

4.4.2 Reducing Greenhouse Gas Emissions

There are more than 2,100 dairies in California with a potential to produce about 40 million cubic feet per day (ft^3/day) of biogas with a potential generation capacity of about 136-140 MW. Assuming 50% CH_4 content in biogas, this represents a potential reduction of approximately 20 million ft^3/day of CH_4 if all biogas is used to generate power. The undeveloped potential generation capacity at California landfills, water treatment digesters, and food digesters is estimated at 600 MW which represents about 85 million ft^3/day of CH_4 . With this post-combustion NOx control with microwave reactivation and biogas upgrading technology, additional biogas can be used to produce electricity and thermal energy to reduce natural gas use in California. Otherwise, the CH_4 will be released to the atmosphere from manure and landfills or flared.

The microwave reactivation technology also has the potential to reduce greenhouse gas emissions attributed to the manufacture and use of carbon in many biogas H_2S and siloxane removal systems. This microwave reactivation can be integrated with the post-combustion NOx control using activated carbon. Carbon is changed out of commercial adsorbers every one to six months. This activated carbon is produced from coal that is first heated to a high temperature to remove VOCs and other hydrocarbons and then treated with steam to activate the pore structure. This process releases significant fossil fuel CO_2 for producing the heat energy needed. The production of one pound of activated carbon generates 2.08 pounds of CO_2 . Furthermore, the bulk activated carbon must be transported, first from a coal mine (typically in Asia) to the biogas site, then from the biogas site to the disposal site releasing additional CO_2 from the transport fuel. If the contaminated carbon is disposed by burning (such as in a biomass plant), all the carbon is released as CO_2 to the atmosphere as the carbon is combusted. If the media used in the microwave process is reactivated 10 times before disposal, it will reduce greenhouse gas emissions due to production, transport and disposal of media by at least 90%.

Manufacturing activated carbon requires 8,000 Btu/lb however, microwave reactivation uses 4,000 Btu/lb, saving about 4,000 Btu per pound of activated carbon recycled. A 300 lb/h microwave reactivation plant could save at least 2,880 million Btu and 749 tons of CO_2 emission per year. This energy savings is equivalent to 4.6 million cubic feet of biogas.

4.4.3 Creating Green Jobs

A successful commercialization of microwave post-combustion NO_x control and biogas upgrading technology will enhance the biogas production from landfills, wastewater treatment facilities, dairy farms, and food processing industries. The microwave technology is expected to reduce the cost of NO_x control and upgrading biogas significantly, increasing the use of biogas for power and fuel production from small biogas sources such as dairy farms and food processing facilities.

The undeveloped potential generation capacity at California landfills, wastewater digesters, and food digesters is estimated at 600 MW. With simpler and cheaper microwave biogas upgrading and exhaust cleanup systems, additional biogas can be utilized to produce electricity and thermal energy to reduce natural gas use in California. The integrated post-combustion NO_x control with microwave reactivation will allow new biogas producers to meet CARB NO_x emission standards with low NO_x removal cost. This will create more biogas production facilities, generating more green jobs.

CHA Corporation is working with Technikon to build a central microwave reactivation facility in California. They can manufacture simpler and cheaper microwave units to be used for reactivating media and upgrading biogas from small sources. CHA sources microwave equipment from Muegge/Gerling Applied Engineering of Modesto, another California company. Within 5 years, about 20 microwave reactivation systems could be built to reactivate activated carbon used for removing H₂S, VOCs, NO_x, and SO₂. Furthermore, the microwave technology will assist new biogas producers to meet new pollution control regulations including CARB 2007 NO_x emission standards. As more systems are installed in California, additional service positions will be required to operate and maintain these systems. Successful commercialization of this microwave technology will create California green jobs and reduce state unemployment.

GLOSSARY

Term	Definition
A/F	Air/Fuel
AD	Anaerobic Digester
CH ₄	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CTC	Carbon Tetrachloride
EAC	Extruded Activated Carbon
FeS ₂	Iron Pyrite
GAC	Granular Activated Carbon
H ₂	Hydrogen
H ₂ S	Hydrogen Sulfide
H ₂ SO ₄	Sulfuric Acid
HALO	Hydrogen Assisted Lean Operation
HCl	Hydrogen Chloride
IC	Internal Combustion
Fe _x O _y	Iron Oxide
LHV	Lower Heating Value
NG	Natural Gas
NOx	Nitrous Oxide
O ₂	Oxygen
P&ID	Piping & Instrumentation Diagram
PFD	Process Flow Diagram
PLC	Programmable Logic Controller
SATS	South Area Transfer Station
SCR	Selective Catalytic Reaction

SiO ₂	Silicon Dioxide
SO ₂	Sulfur Dioxide
U.S. EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

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- CARB Board Meeting, July 9, 2010, Agenda No. 25.

APPENDIX A: Presentation at Project Final Meeting



California Energy Commission

Pre- and Post-Combustion NO_x Control with Microwave Energy


Final Meeting for Grant # PIR-13-006

CHA Corporation

March 29, 2017

Chuck Gentry, CAM
California Energy Commission
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California Energy Commission

Agenda

1. Introductions	All
2. CHA Project Final Meeting	Chuck Gentry
3. Project Outcomes	Chang Yul Cha
1. Project Objectives	
2. Lab Test Results	
3. CleanWorld BioDigester Facility	
4. Field Test Results	
5. Cost Estimation	
6. Conclusions and Recommendations	
7. Project Benefits for California	
4. Questions and Answers	All

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California Energy Commission

Project Final Meeting- Technical Portion

Chuck Gentry

3



California Energy Commission

Project Final Technical Meeting

- Present Project Findings, Conclusions, and Recommendations
- Discuss the Completion of the Project and Success in Achieving its Goals and Objectives.

4



Chang Yul Cha

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- Conduct a field demonstration of integrated microwave technology for pre- and post-combustion NO_x control of bio-gas powered engines
- Demonstrate that this technology will meet the CARB 2007 NO_x emission standards of 5 ppm and remove greater than 90% of SO₂ and VOCs in exhaust

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- H_2S of microwave treated biogas < 0.5 ppm
- Biomethane conversion to H_2 > 70%
- NO_x emission < 5 ppm (CARB 2007 NO_x emission standards)
- SO_2 and VOC removal > 90%
- NO_x reduction by HALO > 70%

1



2



Laboratory Test Results

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H₂S Removal Lab Test Results

Test #	1	2	3	4	5
NG Flow Rate, scfh	9	9	9	9	9
CO ₂ Flow Rate, scfh	3.12	3.2	3.2	3.2	3.2
Airflow Rate, ccf/min	87.6	0	87.6	97.6	0
Microwave Power, kW	200-300	0	100	200	200
Inlet H ₂ S Conc., ppm	1,300	1,300	1,300	1,600	1,500
Outlet H ₂ S Conc., ppm	0	1,100	200	0	1,100
H ₂ S Removal, %	100	15.4	84.6	100	26.7

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Lab Testing for Steam Reforming

- Goals
 - Determine the maximum tail gas flow rate and minimum ratio of steam to methane that provides 70% CH₄ conversion
 - Test the operational performances of three microwave reactors; H₂S removal, steam reforming, water gas shift

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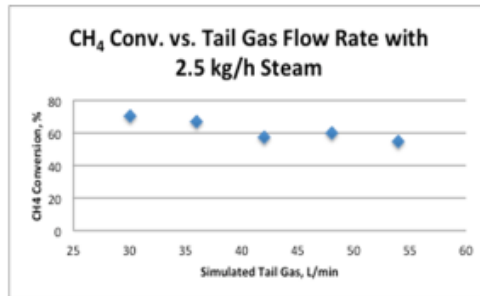
Microwave Steam Reforming System



12



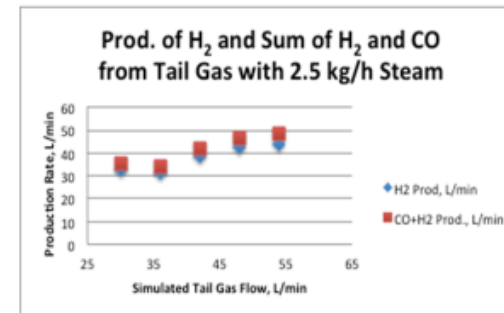
CH₄ Conversion of Simulated Tail Gas



13



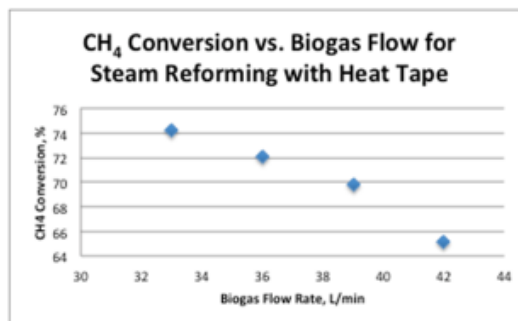
Hydrogen Production from Simulated Tail Gas



14



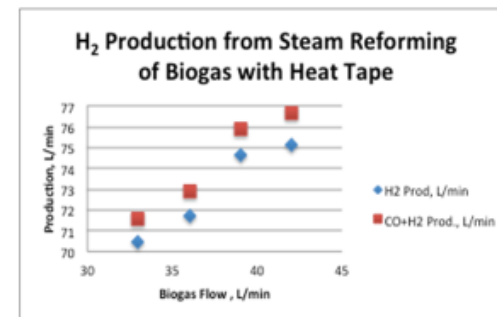
CH₄ Conversion for Steam Reforming of Simulated Biogas



15



Hydrogen Production from Steam Reforming of Simulated Biogas



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CleanWorld

Josh Rapport

17



CleanWorld Successes: Sacramento BioDigester



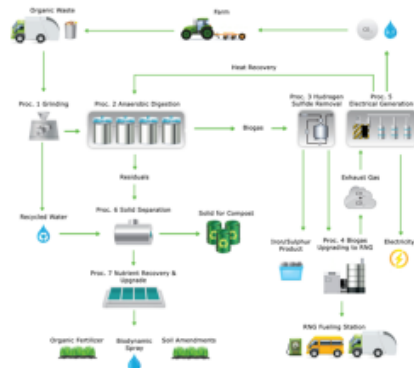
Commissioned: January 2013

- Diverts 10,000 tons/year of food waste, producing RNG to fuel **10 Atlas Disposal waste trucks**
- Scaling up to process **40,000 tons/year** to produce 700,000 diesel gallons equivalent/year for **area fleets**
- Produces valuable soil amendments for **area farms**

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CleanWorld Technology



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CleanWorld's SATS Facility

- Main product is the compressed natural gas (CNG); recovering 120-cfm CH_4 from 300-cfm biogas containing 60% CH_4 and 40% CO_2 .
- 190kW IC engine runs with 50-cfm biogas to supply electricity onsite
- SCR is installed to remove NO_x from exhaust but did not meet the NO_x emission standards.

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Field-Testing of Pre- and Post-Combustion NO_x Control

Chang Yul Cha

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Container and Post-Combustion NO_x Control System



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Pre-Combustion NO_x Control

- Hydrogen Assisted Lean Operation (HALO) provides ultra lean combustion conditions to reduce the peak flame temperatures and significantly decrease NO_x emissions.
- TIAX applied HALO to NG-fired engine and obtained stable engine operation at ultra-lean (Air/Fuel = 2) conditions and reduced NO_x emission to about 10-ppm.
- HALO has not been tested in the field.

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H₂S Removal Test

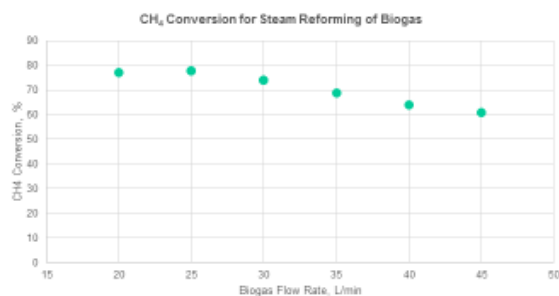
- H₂S removal tests were conducted using 106 and 164 L/min (3.8-5.8-cfm) biogas containing 20 ppm H₂S at 3-kW microwave power.
- H₂S in biogas was destroyed and was not detected with Draeger tube.

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California Energy Commission

Microwave Steam Reforming of Biogas- 47% CH₄ and 53% CO₂

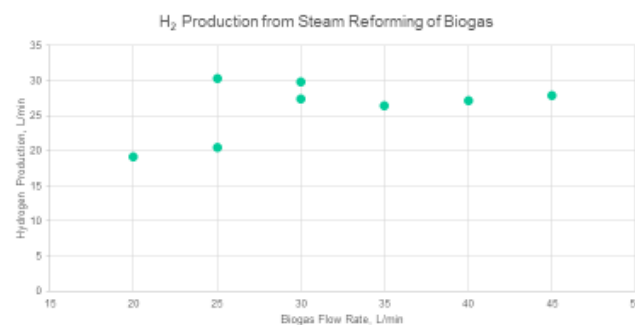


25



California Energy Commission

Microwave Steam Reforming of Biogas- 47% CH₄ and 53% CO₂



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California Energy Commission

Difficulties with Microwave Steam Reforming of Biogas

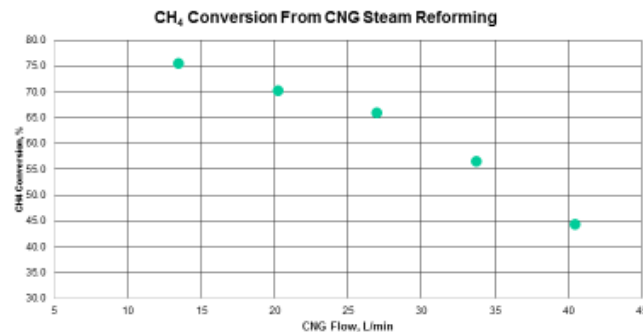
- Heat loss of microwave reforming reactor was too high because of troubles with insulation.
- Methane concentration of biogas (<50%) was much lower than expected.
- Bio-CNG system was shut down because of problems with control system.
- We had to use CNG instead of biogas for generating hydrogen for pre-combustion NO_x control.

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California Energy Commission

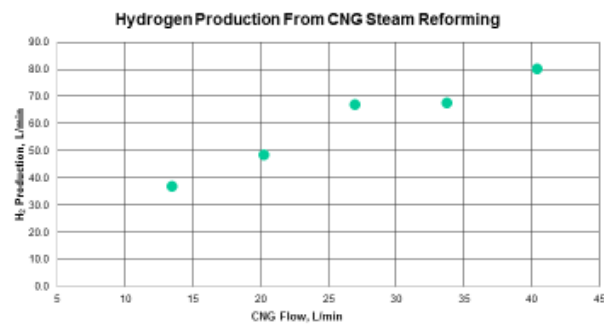
Microwave Steam Reforming of CNG



28



Microwave Steam Reforming Of CNG



29



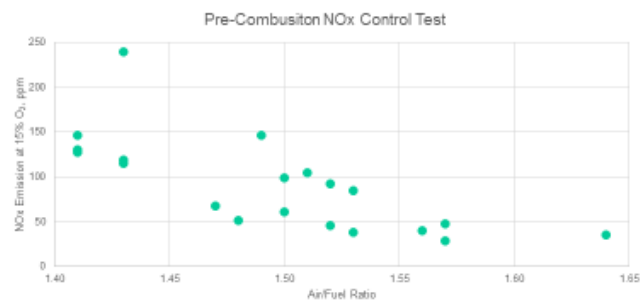
Pre-Combustion NOx Control Test

- 2G engine company did not authorize CleanWorld to change Air/Fuel Ratio
- Western Energy representing 2G changed the air/fuel ratio for us to conduct the pre-combustion NOx control tests for 3 days
- Pre-combustion NOx control tests were conducted using 2.1-2.6 cfm hydrogen injection to the engine running at 100-kW

30



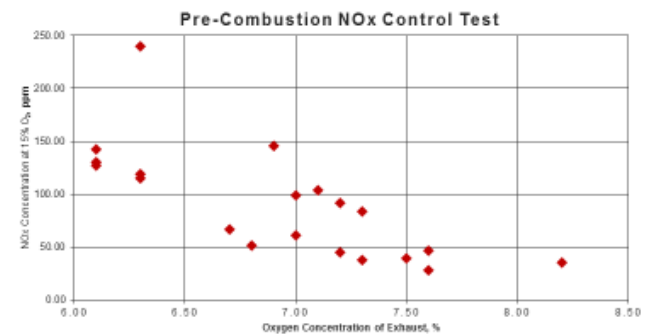
Pre-Combustion NOx Control vs Air/Fuel Ratio



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Pre-Combustion NOx Control vs Exhaust Gas O₂ Concentration



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**Pre-Combustion NOx Control Test Results**

- HALO was applicable to biogas engines
- NOx emission was reduced to 28-35 ppm when the air/fuel ratio increased 1.57-1.64 and exhaust O₂ concentration increased to 7.6-8.2%
- Engine was operated stable with air/fuel ratio at 1.47 with H₂ injection at 2.6-cfm
- NOx emission was reduced from 239 to 67 ppm, 72% reduction in NOx emission

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**Test Target for Post-Combustion NOx Control**

- Demonstrate that post-combustion NOx control with two GAC beds in series could meet the Rule 1110.2 and CARB 2007 NOx emission standards
- Measure NOx Adsorption Capacity of Fresh and Regenerated GAC when Average NOx Emission Level Reaches 5 ppm
- Determine Time for Reactivation of Saturated GAC
- Evaluate Feasibility of Replacing SCR with two GAC beds in series

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**Post-Combustion NOx Control Tests**

- Adsorption test with SCR and engine running with biogas at 190-kW and one GAC bed
- Source testing with SCR and two GAC beds in series
- Long-term adsorption test with two carbon beds in series and engine running with biogas at 100-kW without operating SCR
- Microwave reactivation of NOx-saturated GAC using mobile unit located at CleanWorld site

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**SMAQMD Emission Standards**

Pollutant	Emission Standard and Work Practice
NOx	11 ppmvd corrected to 15% oxygen
CO	250 ppmvd corrected to 15% oxygen
VOC	0.1 g/hp-hr
H ₂ S	40 ppmvd fuel gas influent
Ammonia	11 ppmvd corrected to 15% oxygen

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California Energy Commission

Source Test by Blue Sky Environmental, Inc.

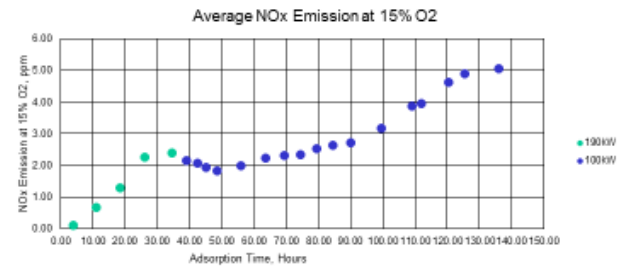
Pollutant	Engine SCR average emissions	Engine SCR plus Carbon Bed average emissions
NOx	22.3 ppm corrected to 15% oxygen (0.22 g/Bhp-hr)	0.4 ppm corrected to 15% oxygen (0.003 g/Bhp-hr)
CO	62 ppm corrected to 15% oxygen (0.37 g/Bhp-hr)	65 ppm corrected to 15% oxygen (0.26 g/Bhp-hr)
VOC	No hydrocarbons greater than C2 were found	No hydrocarbons greater than C2 were found
Ammonia	11.9 ppm corrected to 15% oxygen	0.31 ppm corrected to 15% oxygen

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NOx Emission for Post-Combustion NOx Control without SCR

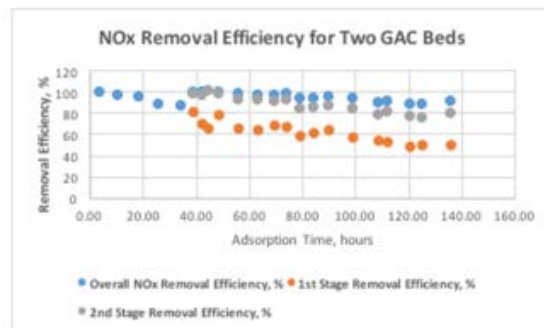


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NOx Removal Efficiency for Post-Combustion NOx Control without SCR



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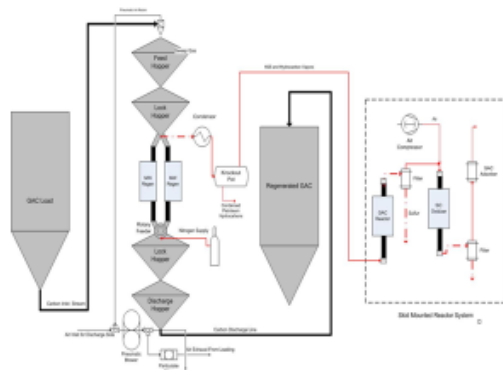
California Energy Commission

Microwave Reactivation of NOx-Saturated Carbon

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PFD for Carbon Reactivation



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Microwave Reactivation of NO_x-Saturated GAC (1st GAC Bed)

- NO_x emission from DeNO_x microwave reactor was 3 ppm in 2-cfm sweep gas through reaction with carbon during reactivation and DeNO_x reactor ($2\text{NO}_x + x\text{C} \rightarrow \text{N}_2 + x\text{CO}_2$).
- Hydrocarbons were destroyed completely in the microwave oxidizer and not detected by THC meter.

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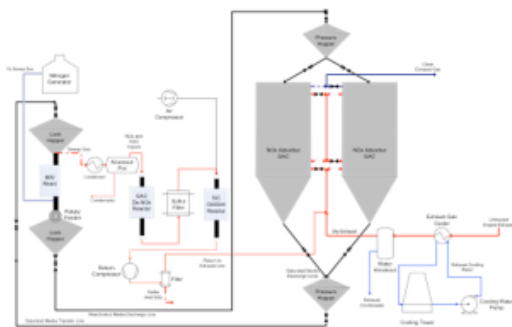


Cost Estimation

- NO_x removal process options for estimating capital and operating costs
 - Pre- and Post-Combustion NO_x Control with H₂ Injection and offsite microwave GAC reactivation
 - Post-Combustion NO_x control with two GAC beds in series with offsite microwave reactivation
 - Integrated Post-Combustion NO_x Control with Onsite Microwave Reactivation

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Integrated Post-Combustion NOx Control with Microwave Reactivation



Capital Cost, \$/kW

Process Option	Capital Cost, \$/kW
Pre- and Post-Combustion NO _x Control	718
Post-Combustion NO _x Control with Two GAC Beds	204
Integrated Post-Combustion NO _x Control	570

NOx Removal Cost

Technology	\$/ton NOx removed	\$/1000 B3 Biogas Consumed	Cents/kWh Per Produced	Pollution Standards Achieved
CHA Microwave System for Pre- and Post-Combustion	24,100	2.66	4.8	Rule 1110.2 CARB 2007
Post-Combustion NOx Control with GAC Beds	31,000	3.21	5.8	Rule 1110.2
CHA Integrated Post-Combustion NOx Control with Microwave Reactivation	9,200	1.02	1.8	Rule 1110.2 CARB 2007
SCR +Oxidation Catalyst, Post-Combustion	27,000	2.80	5.0	Rule 1110.2
NOx Tech, Post-Combustion	25,000	2.59	4.7	Rule 1110.2

Preliminary Commercialization Concept

- CHA and Technikon agreed to form a new company to commercialize CHA's microwave reactivation facilities
- Build a 300 lb/h microwave reactivation system at SATS Digester site
- Market our NO_x control technology to new and existing anaerobic digester (AD) system suppliers
- Develop an GAC supply service for reactivation and provide replacement GAC totes for customers whose media has become saturated



Results Compared to Goals of Pre-Combustion NOx Control

- Goals: Demonstrate HALO would be applicable to biogas engine and could significantly reduce NOx formation. Specific goals: (1) $\text{H}_2\text{S} < 0.5$ ppm, (2) biomethane conversion to $\text{H}_2 > 70\%$, NOx reduction by HALO $> 70\%$
 - H_2S concentration of microwave treated biogas was not detected with Draeger tube
 - Biomethane conversion to H_2 was greater than 70% for biogas flow lower than 35 L/min
 - NOx reduction by HALO was greater than 85%, from 239 ppm to 28-35 ppm with Air/Fuel Ratio = 1.57-1.64 and O_2 in exhaust = 7.6-8.2%. Stable engine operation was obtained by injecting 2.6-cfm H_2 with Air/Fuel ratio of 1.47. The NOx emission was 67 ppm, 72% reduction

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Results Compared to Goals of Post-Combustion NOx Control

- Goals: Meet the Rule 1110.2 and CARB 2007 NOx emission standards. Specific goals were to achieve the average NOx emission less than 5 ppm and SO_2 and VOCs removal efficiency greater than 90%
- Throughout field testing period the average NOx emission did not exceed 5 ppm, meeting Rule 1110.2 and CARB 2007 NOx emission standards.
- NOx saturated GAC was reactivated successfully in the 50 lbs/h microwave reactivation unit. NOx concentration of 2-cfm sweep gas from DeNOx microwave reactor was 3 ppm. Total hydrocarbon concentration in microwave oxidizer was negligible.
- SO_2 and VOCs were not detected in the carbon bed outlet
- Integrated post-combustion system is the most cost effective NOx control technology

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Conclusions – Pre-Combustion Control

- Microwave-GAC reactor was very effective in destroying H_2S
- Microwave steam reforming provide the biomethane conversion to H_2 greater than 70% for biogas flow lower than 35 L/min. Microwave reactor must be redesigned to reduce heat loss and handle higher biogas flow rate
- Microwave steam reforming can be applied for economical onsite H_2 generation for pre-combustion NOx control and fuel cells
- Application of HALO is effective for a biogas engine to reduce NOx formation. Greater than 70% of NOx formation was reduced by injecting H_2 into engine inlet. Because of very high H_2 requirement, HALO alone is not economical NOx control technology

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Conclusions – Post-Combustion Control

- Post-combustion NOx control with two GAC beds in series was very effective to meet the Rule 1110.2 and CARB 2007 NOx emission standards
- Reducing superficial gas velocity in GAC bed increased NOx removal rate
- GAC removed ammonia and VOCs from exhaust
- NOx and hydrocarbons released during the reactivation of NOx-saturated GAC were completely destroyed by microwaves in DeNOx and oxidizer
- Integrated post-combustion NOx control with microwave reactivation is the most cost effective NOx control method to meet CARB 2007 NOx emission standards

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Recommendations

- Conduct the field-testing of microwave based biogas cleanup to determine the economic and technical feasibility.
- Perform detailed technical and economic feasibility study for central microwave reactivation
- Install an integrated post-combustion NO_x control with microwave reactivation and demonstrate that this technology could be BACT for CARB 2007 NO_x emission standards

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Project Benefits for California

- The microwave-based technology allows CARB 2007 emission standards to be met, making biogas cleaner and more acceptable in populated communities.
- Extension of the technology can convert ANY fuel gas (biogas, methane, propane) onsite to H₂ for use in fuel cells or fuel cell vehicles.
- With the microwave technology, additional biogas can be utilized to produce electricity to reduce natural gas use and reduce the release of greenhouse gas (CH₄) from manure digesters and landfills.
- The central or onsite microwave reactivation technology will allow the recycle of activated carbon that will reduce the greenhouse gas emissions attributed to the manufacturing of activated carbon and disposal of used carbon.
- The construction and operation of microwave reactivation and biogas upgrading technology will create green jobs.

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Questions & Answers Final Remarks

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Thank You!

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